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PHYSICAL AND CHEMICAL MEASUREMENTS OF WASTE WATER STABILIZATION LAGOONS DURING WINTER OPERATION

ABSTRACT

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Oxidation-reduction potential, pH and dissolved oxygen content were measured at the city waste stabilization lagoons, Laramie, Wyoming, from November 17, 1965 until January 18, 1966. These measurements were correlated with air and water temperatures and solar radiation of the same period. Tabular results are presented and discussed.

PHYSICAL AND CHEMICAL MEASUREMENTS OF WASTE WATER STABILIZATION LAGOONS DURING WINTER OPERATION

by

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CHAPTER I

INTRODUCTION

Since the early part of this century stabilization lagoons have been in use for primary treatment of raw sewage and also as secondary or tertiary treatment units. Terms such as waste stabilization lagoons, waste stabilization ponds, sewage oxidation lagoons and oxidation ponds are often used interchangeably. It was generally agreed at a symposium in Kansas City, Missouri, August 1-5, 1960, on wastes stabilization lagoons, that the term "waste stabilization lagoons" refers to treatment of raw sewage or other wastes as differentiated from "oxidation ponds" or "oxidation lagoons" which refer to secondary or tertiary treatment.[1*]

The stabilization process consists largely of sedimentation, precipitation of organic materials and the interaction of bacteria and algae. Bacteria digest and oxidize the constituents of the waste. The resulting soluble nutrients, principally carbon dioxide, are utilized by algae which liberate oxygen through photosynthetic action. The oxygen in turn is used by the bacteria.[2]

The principle advantage of waste stabilization lagoons and oxidation ponds is the lower capital cost and lower operating cost which are usually less than half for equivalent treatment plants. Other advantages are ease of expansion, permitting additions in stages when needed, and recovery of lagoon property if subsequent conversion is made to a more conventional treatment plant.[1]

*Superscript Numerals Refer to the Selected List of Reference

Compared with effective conventional treatment works, properly operated and maintained, the lagoon or oxidation pond may have the following disadvantages:[2]

1. More disagreeable odors produced under circumstances such as overloading and for short periods following spring breakup of ice cover and during prolonged cold weather.

2. Greater potential for disease vectors such as mosquitoes transmitting encephalitis.

3. Greater difficulty in effective disinfection for control of disease transmission.

It is the first disadvantage which provided the basis for the present study. The symbiotic cycle (stabilization process) mentioned earlier is only continuous under summer conditions. During winter operation where ice cover is encountered the algal photosynthesis ceases for lack of light, and aerobic processes give way to anaerobic processes when the dissolved oxygen in the water becomes exhausted. Aerobic organisms can only utilize oxygen that is dissolved or free. Anaerobic organisms can draw upon the oxygen of the inorganic and organic matter. The gases of anaerobic decomposition are then released to the water and escape to the atmosphere. During the winter period the ice layer serves as a barrier between the pond and the atmosphere so that nuisance odors which develop are not liberated from a large area until the ice cover breaks up in the spring.

Beside the fact that lagoon odor is a principle objection to stabilization lagoons they have a comparatively low rate of oxidation under anaerobic conditions. These objections may be overcome, however, by installation of diffused or mechanical aeration systems in the lagoons.

The literature indicates that several studies have been conducted and that the aerated lagoon provides an effective and economical means of waste water treatment.[3] The literature also indicates that very little if any consideration has been given to the control of aeration.

The objective of this study was to determine if any correlation exists between certain chemical and physical parameters of waste water treatment utilizing stabilization lagoons that may, in turn, lead to future research in providing a quantatative measure of aeration requirements. The parameters chosen for this study were oxidation-reduction potential, hydrogen ion content (pH) and dissolved oxygen content. These in turn were to be correlated with air and water temperatures and solar radiation. The period of study was from November 17, 1965 to January 18, 1966.

CHAPTER II

OXIDATION-REDUCTION MEASUREMENTS

Originally, oxidation processes were considered to be those in which oxygen was added, and reduction those processes in which oxygen was removed. This definition, however, was found to be inadequate in explaining certain reactions. Oxidation and reduction are now defined in terms of electron transfer. In oxidation the substance oxidized suffers the loss of electrons and in reduction the reduced substance gains electrons. Since an oxidation-reduction reaction involves an electron transfer, a potential change results which can be a measure of certain chemical reactions. It is considered to also be a quantitative measurement of biological systems.

The electrical measurement of this potential is based on a cell, or rather two half-cells, one half of which is the sample solution and the other half-cell a standard reference electrode. The latter is normally a hydrogen electrode whose potential has been arbitrarily assumed as zero volts. However, due to difficulties inherent with the use and operation of the hydrogen reference electrode, it has been common practice to utilize a silver-silver chloride electrode.[4]

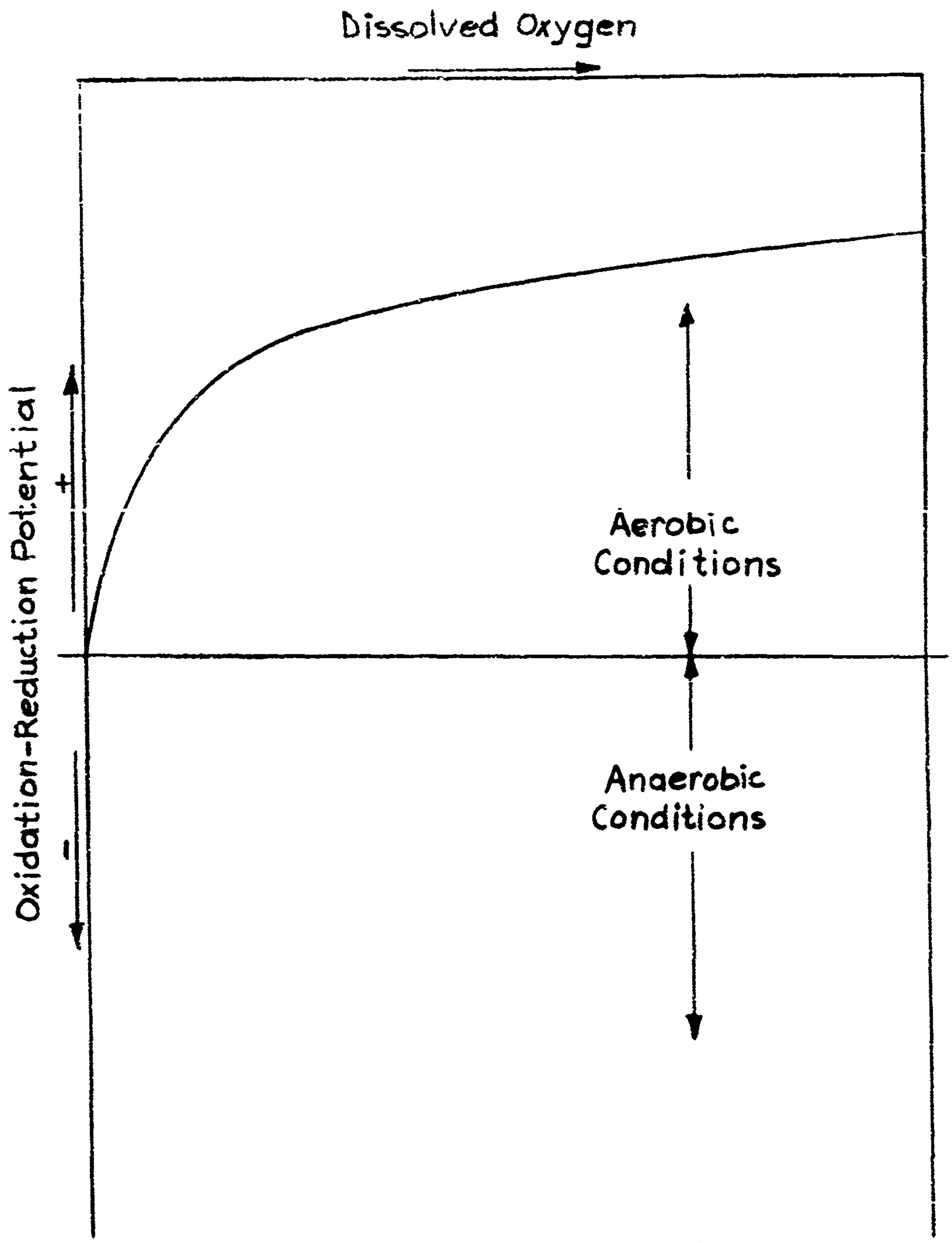
In general terms, oxidation-reduction potentials (ORP) express a mathematical relationship between oxidants and reductants in solution. It is a measure of the intensity of oxidation and not a quantitative measure of oxidizing or reducing capacity. The higher the concentration of oxidants the more positive the potential; the higher the concentration of reductants the more negative the potential.

This relationship has a direct practical significance in biological processes in that positive potentials represent an aerobic or oxidizing environment while negative potentials represent an anaerobic or reducing environment.[5] A qualitative comparison between ORP and dissolved oxygen (DO) is presented in Figure 1. The rate of change of ORP is much greater at very low levels of dissolved oxygen. In a biological system at higher levels of DO, the ORP does not change as rapidly with a change in concentration of oxidants.[6]

Oxidation-reduction potential measurements have been given considerable consideration by investigators for control of sewage treatment operations. The profession, however, has been slow to utilise the ORP concept, possibly due to it being poorly understood. Among the wide variety of applications are monitoring influents, odor control, aeration control and digestion control. Several studies have been conducted in the control of aeration of activated sludge processes, and indications are that a great potential lies in the use of ORP in the control of aeration of the waste stabilization ponds which are quite common in the smaller communities in the midwestern part of the United States and elsewhere. The literature indicates that very little study, if any, has been given to this application.

Theory[7,8]

In the middle of the last century it was generally accepted that electrical energy of a reversible cell was equal to the chemical energy, measured as heat, of the reaction occuring in the cell. It was realized by J. W. Gibbs (1875), that electrical energy of a reversible cell is equal to the free energy change. In a galvanic cell, chemical energy or a related form of potential energy, is converted into electrical energy.



Qualitative Relationship
Between ORP and DO

Figure 1

To obtain the mathmatical expression of the oxidation-reduction potential, it is necessary to start with basic thermodynamic functions. In order that the electrical energy may be related thermodynamically to the energy of the process occuring in the cell it is essential that the latter should behave reversibly in the thermodynamic sense.

By applying the laws of thermodynamics to a closed system the following function can be obtained:

$$F = U + pV - TS^{*}. \qquad (1)$$

The quantity "F" is called the thermodynamic potential, the Gibbs function or free energy.

Differentiation of (1) gives

$$dF = dU + pdV + Vdp - TdS - SdT. \qquad (2)$$

Assuming the process to be reversible, at constant temperature and at constant volume, (2) becomes

$$dF = Vdp \qquad (3)$$

To be able to integrate (3) it is necessary to have an equation relating p and V; for one mole of an ideal gas, $pV = RT^{*}$. It follows then that

$$\Delta F = RT \ln \frac{p_2}{p_1}. \qquad (4)$$

When considering a reversible chemical reaction, if the constituents are not at equilibrium but at certain arbitrary concentrations, there is a definite change of free energy as a result of the conversion of the

---

*U = Internal Energy
p = Partial Pressure
V = Volume
T = Temperature
S = Entropy
R = Universal Gas Constant

reactants A, B, etc., to the products L, M, etc. Imagine a container in which various gases taking part in the reaction are present at equilibrium, and let the partial pressures be $(p_A)_e$, $(p_B)_e$, etc., and $(p_L)_e$, $(p_M)_e$, etc., the subscript "e" indicating equilibrium conditions. Suppose v_A moles of a reactant A at an arbitrary pressure p_A are transfered isothermally and reversibly into the container through the wall which is permeable to A; the free energy change, assuming ideal gas, is then

$$\Delta F_A = v_A RT \ln \frac{(p_A)_e}{p_A}. \tag{5}$$

The same analogous expression applies for all the other reactants that are transferred at the same time. It may be assumed that the products are simultaneously withdrawn isothermally and reversibly. The net increase of free energy for the whole process is

$$\Delta F = \left[v_A RT \ln \frac{(p_A)_e}{p_A} + v_B RT \ln \frac{(p_B)_e}{p_B} + \ldots\right] - \left[v\ RT \ln \frac{(p_L)_e}{p_L} + v\ RT \ln \frac{(p_M)_e}{p_M} + \ldots\right]. \tag{6}$$

This equation may be written in the form

$$\Delta F = RT \ln \frac{(p_L)^{v_L}(p_M)^{v_M} \ldots}{(p_A)^{v_A}(p_B)^{v_B} \ldots} - RT \ln \frac{(p_L)_e^{v_L}(p_M)_e^{v_M} \ldots}{(p_A)_e^{v_A}(p_B)_e^{v_B} \ldots}. \tag{7}$$

If all the substances taking part in a reaction are in their respective standard state of unit activity, the standard free energy change is

$$-\Delta F^o = RT \ln \frac{(p_L)_e^{v_L}(p_M)_e^{v_M} \ldots}{(p_A)_e^{v_A}(p_B)_e^{v_B} \ldots}. \tag{8}$$

Thus, equation (7) can be reduced to

$$\Delta F = \Delta F^o + RT \ln \frac{(p_L)^{v_L}(p_M)^{v_M} \ldots}{(p_A)^{v_A}(p_B)^{v_B} \ldots}. \tag{9}$$

Glasstone states that for any system, whether ideal or not,

$$K = \frac{(a_L)^{v_L}(a_M)^{v_M} \ldots}{(a_A)^{v_A}(a_B)^{v_B} \ldots}, \tag{10}$$

"a" being activities and K being a constant. If the system is ideal, the activities may be replaced by the respective partial pressures (as in equation 9). For a real system these activities may be considered to be the oxidized state and the reduced state.

When the reactants form part of a galvanic cell the change in free energy is equal to the electrical work done; so that

$$-\Delta F = nFE^{*}. \tag{11}$$

Consequently, if all the substances contained in the cell are in their respective standard state of unit activity, the E.M.F. is the standard value E^o for a given cell; the standard free energy is therefore

$$-\Delta F^o = nFE^o. \tag{12}$$

The negative signs imply a decrease of free energy. Combining these results with (9), and considering the partial pressures of the products and reactants as activities of reductants and oxidants of a real system, it is seen that

$$E = E^o - \frac{RT}{nF} \ln \frac{[Red]}{[Ox]}. \tag{13}$$

Thus, (13), expresses mathematically the basic reaction of the oxidation-reduction potential where R is the gas constant, T the absolute temperature, F the faraday, and n the number of electrons involved in the transformation of the oxidant to the reductant. E^o is the voltage of the

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*n = The Number of Electrons Involved in the Reaction
F = The Faraday (96,540 Coulombs)
E = The Electrode Potential

reference electrode which is constant. [Red] is defined as the concentration of the reductants and [Ox] is defined as the concentration of the oxidant. The oxidation-reduction reaction may be represented as

$$Ox + e \rightleftharpoons Red. \tag{14}$$

When working with a biological system only concentrations of total oxidants and total reductants are determinable because it is impossible to determine the individual oxidants and reductants. However, to understand the potential better, an analogy can be made with the electrode for the ferrous-ferric system

$$Fe^{+++} + e \rightleftharpoons Fe^{++} \tag{15}$$

and hence by (13), the potential is given by

$$E_{Fe^{++},Fe^{+++}} = E^{o} - \frac{RT}{nF} \ln \frac{a_{Fe^{++}}}{a_{Fe^{+++}}} . \tag{16}$$

Up to this point only systems of constant pH have been considered. When the hydrogen ion concentration is allowed to vary, it affects oxidation-reduction systems by altering the ionic equilibria.

To be consistant the reductant must be identified as an anion (or the oxidant as a cation). The effect of pH may then be illustrated by means of the simple case

$$Ox + e = R\bar{e}d, \tag{17}$$

for which the equilibrium equation

$$K = \frac{[Ox][e]}{[R\bar{e}d]} \tag{18}$$

is assumed. For dilute solutions one may assume that the total reductant, S_r, is the sum of the anions and the non-ionized acid. That is,

$$[S_r] = [H\ Red] + [R\bar{e}d]. \tag{19}$$

The equilibrium equation for the acid dissociation of the reductant is

$$K_a = \frac{[\text{Red}][H^+]}{[\text{H Red}]} . \tag{20}$$

Combining (19) with (20) and solving for $\overset{=}{\text{Red}}$, gives

$$[\overset{=}{\text{Red}}] = \frac{[S_r]K_a}{[H^+] + K_a} . \tag{21}$$

Equations (13) and (21) now yeild

$$E = E^o - \frac{RT}{nF} \ln \frac{[S_r]}{[S_o]} - \frac{RT}{nF} \ln \frac{K_a}{[H^+] + K_a} . \tag{22}$$

which is the general electrode equation holding at all values of pH.

It should be noted that, if the hydrogen ion concentration is kept constant, the last term in equation (22) becomes a constant, so that the general electrode equation (13) holds true.

Applications

During the past two decades many investigators have considered the use of ORP measurements for the control of operations in sewage and industrial waste treatment systems.[6] Hood[10] states that the following are some of the more obvious applications:

1. Detection of deposits, growth or other conditions in the sewer system or pumping stations leading to septicity or sulfide production; for observation of the effectiveness of sulfide control measures.

2. Detection of industrial wastes.

3. Detection of toxic substances or conditions.

4. Establishment of proper sludge pumping schedules at primary sedimentation tanks, through the detection of excessive sludge accumulations.

5. Detection of over-long detention periods at primary tanks.

6. Determination of internal conditions within trickling and sand filters.

7. Determination of conditions in activated sludge aeration tanks.

8. Detection of excessive sludge blanket in activated sludge settling tanks.

9. Determination of conditions in sludge digestion tanks.

Nussberger[10] summarizes ORP measurements as providing a tool for control of aeration in the activated sludge processes and the step-aeration process because of the following observed effects:

1. The oxidation-reduction potential of the aeration tank liquor is greater at the end of a pass than at the beginning of the pass, provided of course, that the air supply is sufficient.

2. Addition of sewage to aeration tank liquor depresses the oxidation-reduction potential of the tank liquor.

3. If the oxidation-reduction potential of the aeration tank liquor is depressed to a very low value by the addition of too large a volume of sewage, it may not recover in value during the subsequent period of aeration.

4. If the activated sludge is well oxidized, as shown by a high level of oxidation-reduction potential of the aeration tank effluent, the oxidation-reduction potential of the returned sludge will be high, other factors being equal.

5. Sewage increments may be so distributed among the several aeration tank inlets in the step-aeration process as to give increasing peak values of oxidation-reduction potentials through the aeration tank.

6. Oxidation-reduction potential measurements may be used to control the volume of the sewage added at each point in step-aeration so that it will allow a recovery of oxidation-reduction potential in the subsequent period of aeration to a value slightly greater than that prevailing before the addition of the sewage.

Limitations

Hewitt[8] has found that platinum electrodes are the most reliable of several used by different workers. In most cases, therefore, a platinum surface forms the measuring electrode in an ORP cell. Kehoe and Jones[12] list the following limitations of this electrode:

1. It can be influenced by all oxidants and reductants present.

2. The surface can become mechanically coated to desensitize its performance.

3. The surface can exhibit a memory effect by exposure to strong oxidants or reductants with subsequent residual influence.

4. The pH of the solution influences the net potential measured.

5. The temperature of the solution influences the potential but only slightly.

It is important to realize that a high positive ORP from a biological oxidation system, operating without internal application of oxidizing agents, may be interpreted as indicating successful operation. However, concentrated sulfuric, glacial acetic, chlorine solution, etc. all are systems in which no biological process could function, but they yield high positive ORP values.[10]

CHAPTER III

pH MEASUREMENTS

Theory[8,9]

In its simplest definition, pH can be defined as a measure of the effective acidity or alkalinity of a solution. Water itself dissociates to a slight degree to form hydrogen ions (H^+) and hydroxyl ions (OH^-) in equal concentrations. The extent of this dissociation is expressed as the ion product constant of water. At 77°F. (25°C.), the value of this constant is 10^{-14}. In pure water at this temperature, $H^+ = OH^- = 0.0000001$ or 10^{-7} moles per liter. The product of hydrogen and hydroxyl ion concentrations is always 10^{-14} in any dilute aqueous solution at 25°C. If acid is added to the pure water, hydrogen ion concentrations increase while the hydroxyl ion concentration decreases so the product of the two always equals 10^{-14}.

pH is the common logarithm of the reciprocal of the active hydrogen ion concentration expressed in terms of mols per liter. pH can also be expressed as the negative logarithm of this hydrogen ion concentration. Pure neutral water has a hydrogen ion concentration equal to 10^{-7} mols per liter. The negative logarithm of this number is 7. Thus neutral water has a pH of 7. Since the pH expression is logarithmic, there is a 10-fold change in hydrogen ion concentration per unit change in pH. A slightly acidic solution having a pH of 6 contains ten times as many active hydrogen ions as a pH 7 solution. A slightly alkaline solution having a pH of 8 has only a tenth as many hydrogen ions (or ten times as

many hydroxyl ions) as a pH 7 solution. A more strongly acidic solution of pH 2 has 100,000 times more hydrogen ions than a pH 7 solution. The pH index normally is considered to range between pH 0 to pH 14.

The hydrogen electrode was once the main basis for pH determinations and is a special example of an oxidation-reduction electrode as explained in Chapter II. It is not commonly used, however, for biological pH measurements; firstly, because hydrogen may reduce components of the system; secondly, the system requires bubbling hydrogen through it at one atmospheric pressure which introduces difficulties due to frothing and also due to the stripping of carbon dioxide which alters pH values of the system; thirdly, more convenient methods not necessitating the use of hydrogen gas are available.

In practice pH measurements are not determined by absolute potential measurements. They are accomplished by measuring the difference between the potentials of a standard buffer solution and the unknown solution. As with oxidation-reduction potential measurements, a standard reference half-cell is needed to complete the cell and the half-cells are joined by a suitable liquid junction.

The glass electrode has come to be used almost exclusively for electrometric pH measurements in biological work. Essentially this electrode consists of a thin glass membrane which for all practical purposes is permeable only to hydrogen ions so that the difference in potential, of electrodes immersed in the solution on either side of the membrane, is governed by the difference in pH of the solutions. In practice the glass electrode is generally a thin glass bulb blown on the end of a tube. A solution of constant pH with a silver or platinum wire dipping into it is placed inside the bulb.

By applying the general electrode equation, the potential of a cell consisting of a glass electrode and a reference electrode, is given as

$$E = E^{o} - \frac{RT}{F} \ln a_{H^+} \qquad (23)$$

Introducing the definition of pH as $-\ln a_{H^+}$, this becomes

$$E = E^{o} + 2.303 \frac{RT}{F} pH; \qquad (24)$$

therefore

$$pH = \frac{F(E - E^{o})}{2.303 \; RT} \; . \qquad (25)$$

Applications[9]

pH measurements has found wide industrial applications for over two decades. So widespread and varied is the use of the pH equipment that only a few examples will be discussed.

Continuous pH analyzers are valuable in municipal sewage treatment plants for keeping sludge digestion processes within proper pH limits. Out-of-limits pH impairs sludge digestion, reducing the efficiency of this sewage treatment process.

Flocculation is an important step in the treatment of raw water to produce potable water. Adding flocculating agents to the raw water, followed by close pH measurements and control, produces a floc which will coagulate turbidity and other water impurities and settle rapidly. Hard water is often softened by the lime-soda process. Lime (calcium hydroxide) and soda ash (sodium carbonate) are added to hard water to remove calcium and magnesium salts. Following the removal of solids, the pH of the water is continuously adjusted by the addition of either carbon dioxide or acid.

Reagent addition is often controlled with pH analyser and recorder-controllers.

The chemical treatment of raw water and boiler feed water is a most important function in a boiler plant. The maintenance of the proper pH levels in the boiler plants are required for equipment protection and corrosion control. pH instrumentation in such a plant serves as an important control devise.

pH measurements are widely used in other industries such as sugar refining, pulp and paper, food processing, metals and mining and synthetic rubber manufacture in the control of certain processes.

CHAPTER IV

DISSOLVED OXYGEN MEASUREMENTS

Many attempts to utilize electrode systems for oxygen determination in natural waters and wastes have been made. One of the principle problems, however, has been the effect of electroactive or surface active impurities which either react with or poison the sensing device. Mancy and others made a study to develop a more suitable electrode system; the desired characteristics of which include the ability for continuous monitoring for oxygen, long term stability, ruggedness and suitability for field use as well as plant processes, simplicity and ease of operation and maintenance.[13]

Principles Involved[13]

The galvanic cell design shown in Fig. 2 approached the desired characteristics. A thin polyethylene membrane fixed in near contact with the electrode permits rapid diffusion of oxygen to the electrode's surface. The membrane also forms a protective barrier separating the electrode system from the test sample. Because of the high selective permeability of the membrane towards oxygen, measurements for oxygen in the presence of electroactive and surface active impurities that interfere in conventional voltaic cells may be accomplished.

The main design factors that influenced the performance characteristics of the galvanic cell analyzer were as follows:

1. The thickness and permeability of the plastic membrane.

2. The geometry and arrangement of the galvanic couple.

3. The quantity of the electrolyte solution (potassium hydroxide).

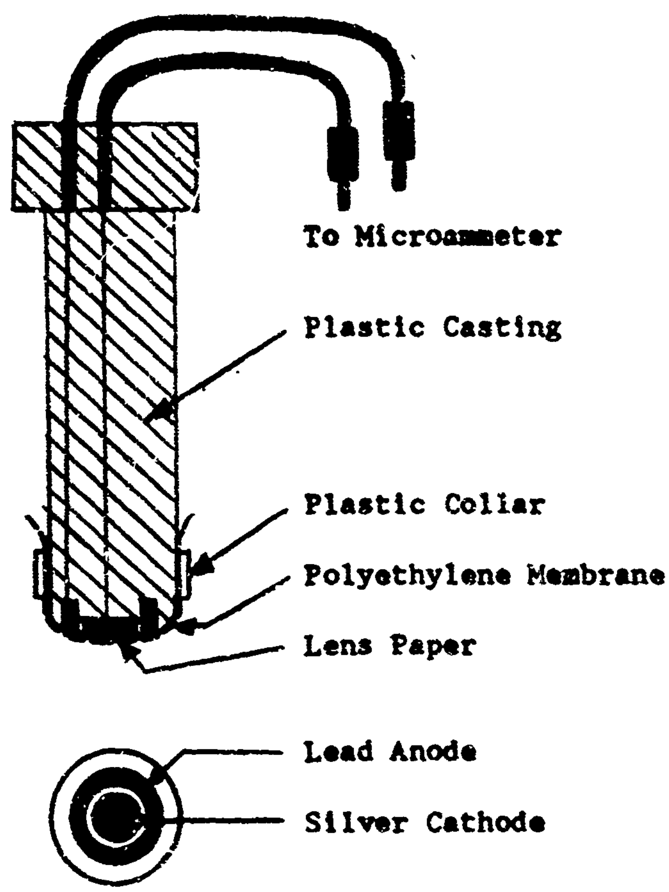

FIGURE 2. The Galvanic Cell Oxygen Analyzer.

Both electrodes are covered with a thin layer of KOH (potassium hydroxide) electrolyte solution contained in a thin electrolyte pad (lens paper). The choice of a lead anode-silver cathode galvanic couple is based on the stability of a silver cathode over the conventional platinum electrode and because the lead anode potential is sufficiently negative to cause spontaneous oxygen reduction without an externally supplied voltage. The KOH solution was chosen as the electrolyte because its conductivity is

high, the residual current in the absence of oxygen is small, and in it, lead ions are soluble, thus maintaining a clean anode surface.

The current generated in this electrode system depends on the steady state of mass transfer of the oxygen across the membrane and on the kinetics of the overall electrochemical process within the galvanic cell. The steady state current generated by this electrode system is given by

$$i_{\infty} = nFA\frac{P_m}{L}C_s \qquad (26)$$

in which

i_{∞} = steady state diffusion current, in amperes

n = number of electrons involved in electrode reaction per mole of electroactive species

A = area of the cathode surface, in sq. cm.

F = faraday (96,540 coulombs)

P_m = permeability coefficient of the plastic membrane, in sq. cm./sec

L = thickness of the plastic membrane, in cm.

C_s = concentration of oxygen in the test sample, moles/ml.

The theory of diffusion current is described in detail by Mancy.[13] It is based on the principle of finite diffusion electrode systems; the membrane placed in close contact with the electrode surface constitutes a rigorously defined diffusion layer. In such electrode systems the membrane helps to maintain stable electrode characteristics in stirred test solutions.

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Analyzer Performance Characteristics[14]

One of the main characteristics of voltammetric membrane electrodes is the relatively high temperature coefficient. This is largely due to

the effect of temperature changes on the permeability characteristics of the plastic membrane. Temperature effects on the electrode reaction kinetics or the electrode potential are relatively small.

The instrument sensitivity ϕ (micro amp/mg/l) varies with temperature, as shown in Fig. 3,

$$\frac{d\phi}{dT} = \frac{\phi}{T^2} m \tag{27}$$

in which m is a constant and T is temperature in degrees Kelvin. If log ϕ is plotted against 1/T, a straight line is obtained. Its equation, derived by integration of equation (27), can be written as

$$\log \phi = \frac{-m}{2.303} \frac{1}{T} + b \tag{28}$$

in which b is the ordinate intercept, and -m/2.303 is the slope. From this, if m and ϕ are determined for one temperature, it is possible to calculate the instrument sensitivity at any desired temperature. Sensitivity is determined from current readout and dissolved oxygen concentration as determined by the Winkler method.

The analyzer requires replenishing periodically which is accomplished by replacement of the membrane and electrolyte pad. After changing the membrane, the analyzer is connected to the microammeter and immersed in an oxygen-free water sample (sodium sulfite solution) for a few hours in order to stablize, after which time the current should fall to 0.2 to 0.5 micro amps. To avoid drying out of the electrolyte solution layer, the analyzer probe should be stored in a bottle or test tube containing sodium sulfite solution or tap water.

A certain amount of care and attention is required for the operation and maintenance of the analyzer. As shown in Fig. 4, the flow of the test

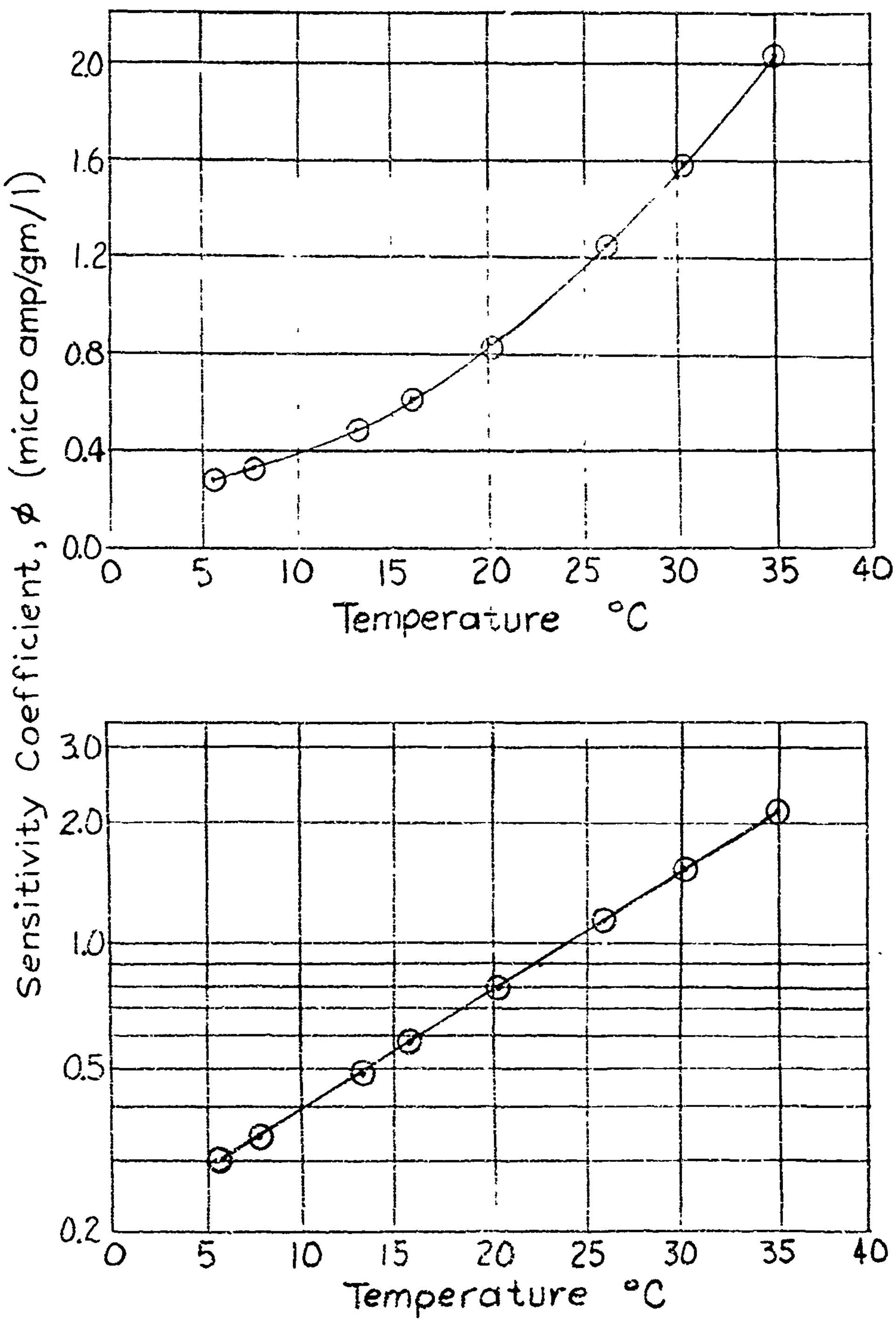


FIGURE 3. Effect of Temperature on Sensitivity Coefficient.

solution near the tip of the analyzer has an effect on the sensitivity. Adequate stirring of the test solution leads to an oxygen concentration at the membrane surface equal to that of the bulk of the solution. Only under this condition will the measured current be directly proportional to the oxygen concentration in the bulk of the test sample.

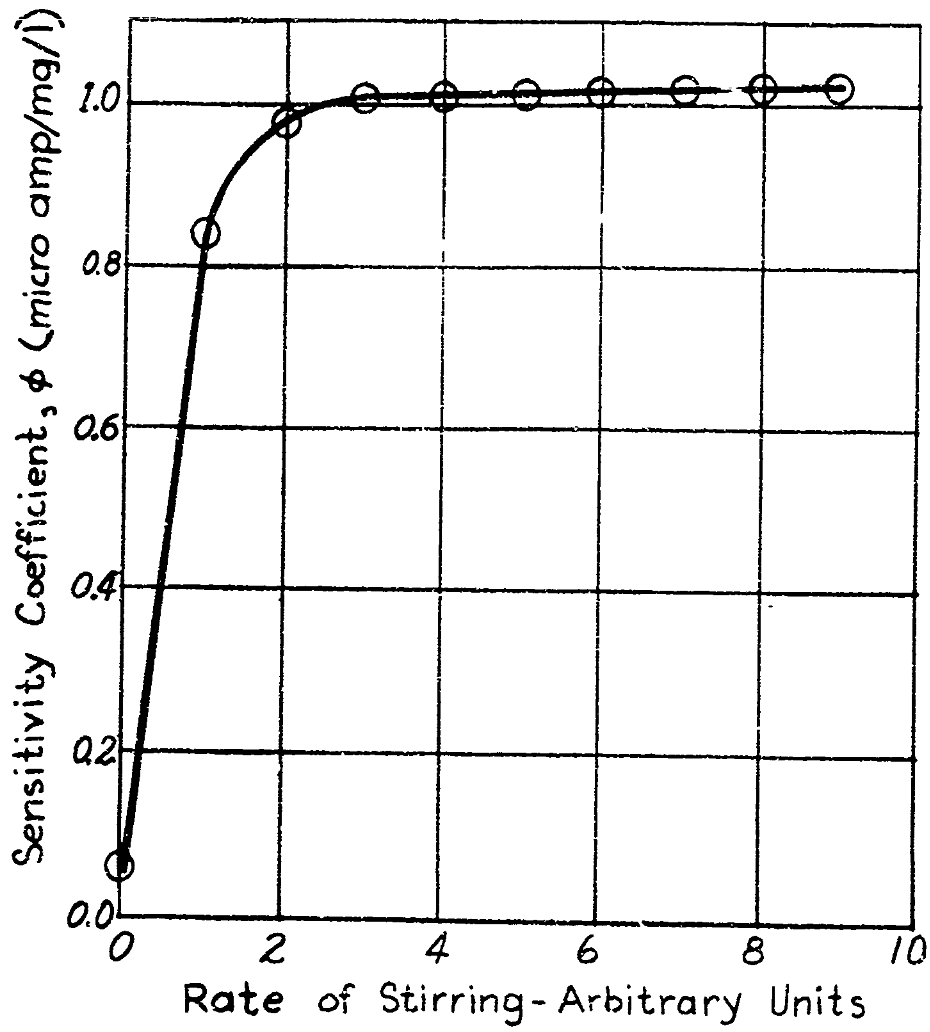


FIGURE 4. Effect of Stirring on Sensitivity.

Applications[13]

The galvanic cell oxygen analyzer has been used successfully for determining the role of oxygen transfer in bubble aeration processes. The electrode system was lowered directly into the aeration column to the desired level. The analyzer was inverted with the surface of the sensing electrode facing upward. When attached to a recorder continuous smooth curves easily read over the normal range of dissolved oxygen concentration were obtained. The procedure permitted convenient measurement of the rate of oxygen transfer in the aeration column without requiring any change of the original volume as a result of sampling.

The simplicity, ruggedness, portability and ease of handling facilitate the use of the galvanic cell oxygen analyzer under variable field conditions. As the analyzer is completely submersible, errors usually caused by sampling difficulties are eliminated. This is especially important for studies performed at different depths where changes in the physical and chemical characteristics of the sample are difficult to prevent when they are brought to the surface. One of the first applications of the galvanic analyzer consisted of obtaining a vertical oxygen profile in a thermally stratified lake and diurnal changes in dissolved oxygen at a predetermined depth. The analyzer has been successfully used for monitoring oxygen in streams as a pollution control measure. A example of this case arose when waste from a paper mill was discharged in a river and it was necessary to evaluate the dissolved oxygen relationship downstream. Several monitoring stations were installed to provide a continuous record of dissolved oxygen. This information in turn was used to control the discharge of the plant effluent.

Chemical methods for measuring dissolved oxygen in activated sludge are not satisfactory; as oxygen is important in the process, its frequent or preferably continuous determination is of great value. With an analyzer it is relatively simple either to check periodically the dissolved oxygen at various points of the plant or to monitor dissolved oxygen changes continuously.

CHAPTER V

FACILITIES AND EQUIPMENT

Sewage Treatment Facility

The City of Laramie sewage treatment facility was chosen for this study because of it's availability and because it is a typical waste water stabilization lagoon which is suitable for an aeration system.

The City of Laramie is located on the Laramie River in Southeastern Wyoming, at an elevation of approximately 7200 ft.. The waste water collection works of the city are divided into a storm drainage system and a domestic system. The storm drains collect the surface runoff and discharge into the Laramie River without being treated. Domestic sewage is collected and delivered into four stabilization lagoons northwest of the city for treatment. The area of the lagoons is 104.4 acres.

The effluent from the lagoons is released over two rectangular weirs, one at each end of the lagoons, see Fig. 5. The south weir is located about 300 yards west of it's river discharge point which is near the Union Pacific Railroad bridge that crosses the Laramie River. The north weir discharge enters the Laramie River about two miles downstream from the south weir discharge point.

The average daily discharge from the lagoons is about 2.0 million gallons (approximately 6 acre-ft.). This was determined from data collected during the summer of 1965 and confirmed during the period of this study.[15]

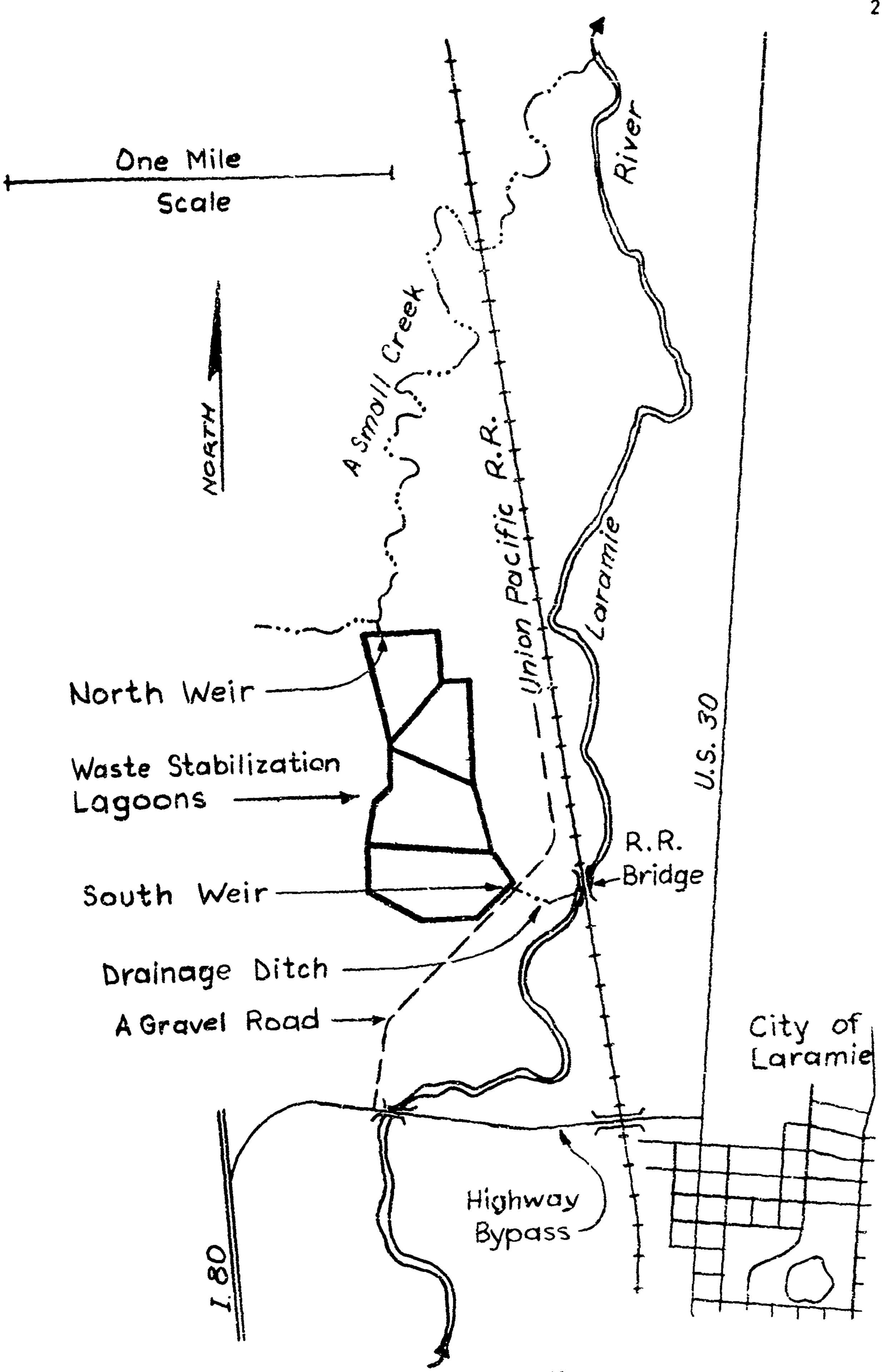


FIGURE 5. Study Area Map.

The oxidation-reduction potential, pH and dissolved oxygen measurements were taken at approximately 20 ft. from the lagoon shore near the south weir, at a depth of one foot from the surface. The depth of the water at this point was about two feet.

Weather Facilities

The solar radiation data and daily air temperatures were obtained from the University Weather Station, Laramie, Wyoming. This information is tabulated in the appendix.

Daily air temperatures were also obtained from the Water Resources Research Institute (WRRI) Weather Station located near the south weir at the city sewage treatment facility. Air temperatures were not available, however, between the 15th and 28th of December and after January 11. A linear regression correlation was made with the University Weather Station for minimum daily temperatures to fill in the missing data. Maximum daily temperatures were taken as the same as those at the University Weather Station; available maximum daily temperature at the lagoon never varied more than one degree from those at the University Weather Station. A plot and tabulation of this information is also in the appendix.

pH Meter[9,16]

pH measurements and oxidation-reduction potential measurements were taken with the Beckman Model N-2 pH meter, manufactured by the Beckman Instruments, Inc. This instrument is fully portable, and designed principally for field use. It is a battery operated meter with a manually operated temperature compensator for sample temperature effects on electrode output. It provides readings over the full 0 to 14 pH range, with a two

FIGURE 6. South Weir Structure and WRRI Weather Station.

position range switch for reading pH values from 0 - 8 and 6 - 14 on two full-color scales. A glass electrode is used in combination with the reference electrode.

Before actual measurements can be taken the instrument has to be standardized with a buffer solution of a known pH. This is accomplished by setting the temperature compensator to the temperature of the buffer solution and then turning the range switch to 0 - 8 or 6 - 14 position depending on the pH of the buffer. Adjust the "Standardize" control until the meter needle indicates the pH of the buffer solution. Rinse the electrodes with distilled water and dry; place the electrode in the sample. Set the temperature compensator to the temperature of the sample solution. Turn range switch to the appropriate pH range and read the pH of the sample.

There is a distinct similarity between pH measurements and oxidation-reduction potential (ORP) measurements. Thus the Beckman Model N-2 pH meter was utilized for both measurements. The Model N-2 can be used to measure voltages from -420 to +420 millivolts by using a platinum electrode in combination with the reference electrode. The pH scale reading is simply converted to millivolts by the use of the formula

$$(7 - \text{pH scale reading})(60.0) = \text{mv.}$$

The operation to obtain ORP measurements is as follows. Set temperature compensator to 29°C., regardless of the actual temperature of the sample solution. Turn range switch to check and set meter to 7.00 pH with "Standardize" control. Turn range switch to appropriate pH range and convert pH scale reading to millivolts with the use of the above formula.

For this study, daily measurements of ORP and pH were obtained and are tabulated in the appendix. All measurements were taken in the middle

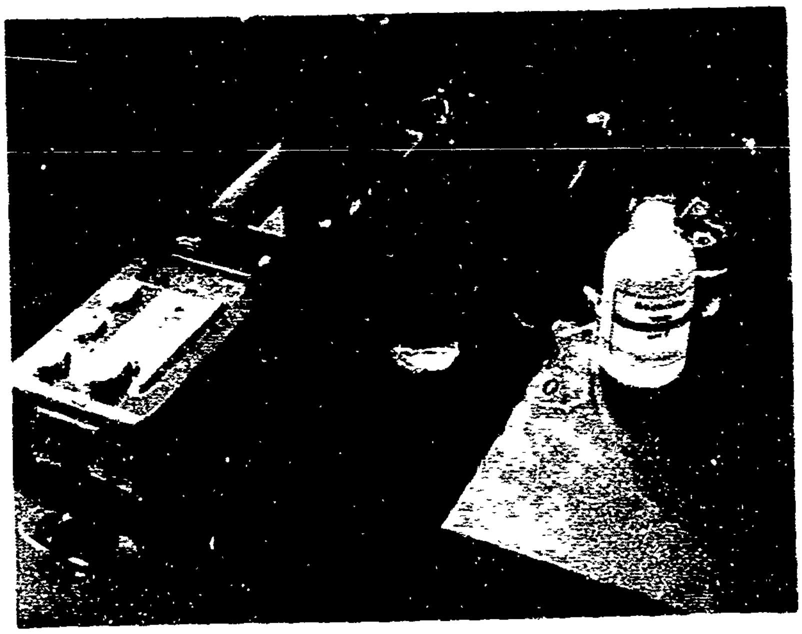


FIGURE 7. pH Meter

of the afternoon of the days indicated. Measurements were taken less frequently after January 1 and suspended after January 18, because they appeared to be stable. This was confirmed by measurements taken several days prior to April 4, 1966, at which time the oxidation-reduction potential went positive indicating aerobic conditions.

Dissolved Oxygen Analyzer[17]

Dissolved oxygen measurements were taken with a galvanic cell oxygen analyzer. The analyzer instrument couples ease of operation maintenance with the capability of continuous analysis of oxygen in natural waters and waste waters. It is a portable unit manufactured by the Precision Scientific Company for use in the laboratory, field or plant.

The oxygen analyzer has a sensitivity of ±0.1 ppm. The flow velocity required past the electrode is one foot per second resulting in a response time of 90% in one minute or less. The thermistor used with the analyzer has a 99% response in 30 seconds with an accuracy of ±0.1°C.

The operation procedure of the instrument is as follows. The probe is placed in the sample container, stream or body of water to be analyzed. The 5-way control switch is turned to "temp. adj.". The meter needle is adjusted until it reads 40°C. The switch is then turned to "temp. read" and the temperature of the sample read from the meter. With the switch at "oxygen" the oxygen reading is taken. This reading is adjusted by a previously determined conversion factor to obtain the actual oxygen content. After approximately two weeks of use, the probe must be renewed by replacing the membrane and electrolyte pad saturated with potassium hydroxide electrolyte solution.

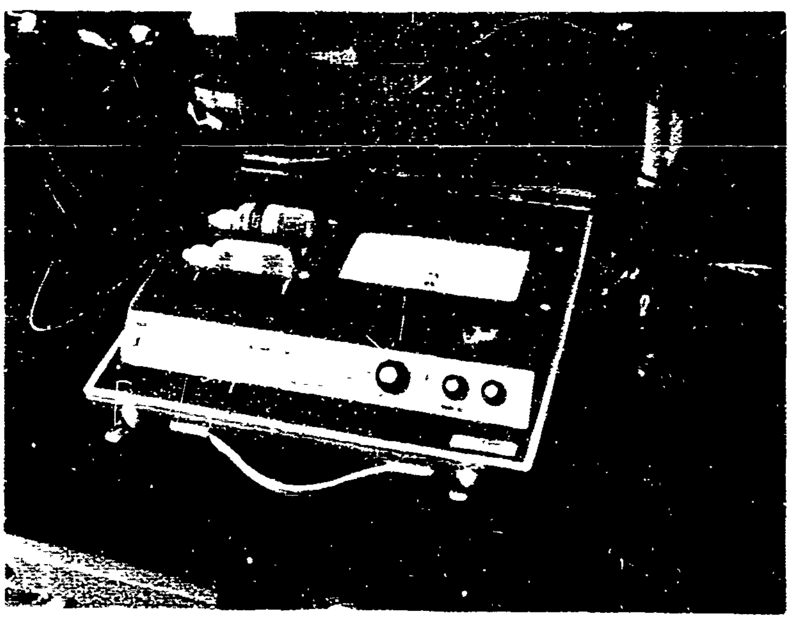


FIGURE 8. Dissolved Oxygen Analyzer.

For this study, daily measurements of dissolved oxygen and water temperature were obtained and are tabulated in the appendix. All measurements were taken in the middle of the afternoon of the days indicated. After the stabilization process changed from aerobic to anaerobic which occured on December 18, 1965 the measurements were taken less frequently. After this date, however, the dissolved oxygen content remained at zero as anticipated, until April 4, 1966 at which time the stabilization process reversed.

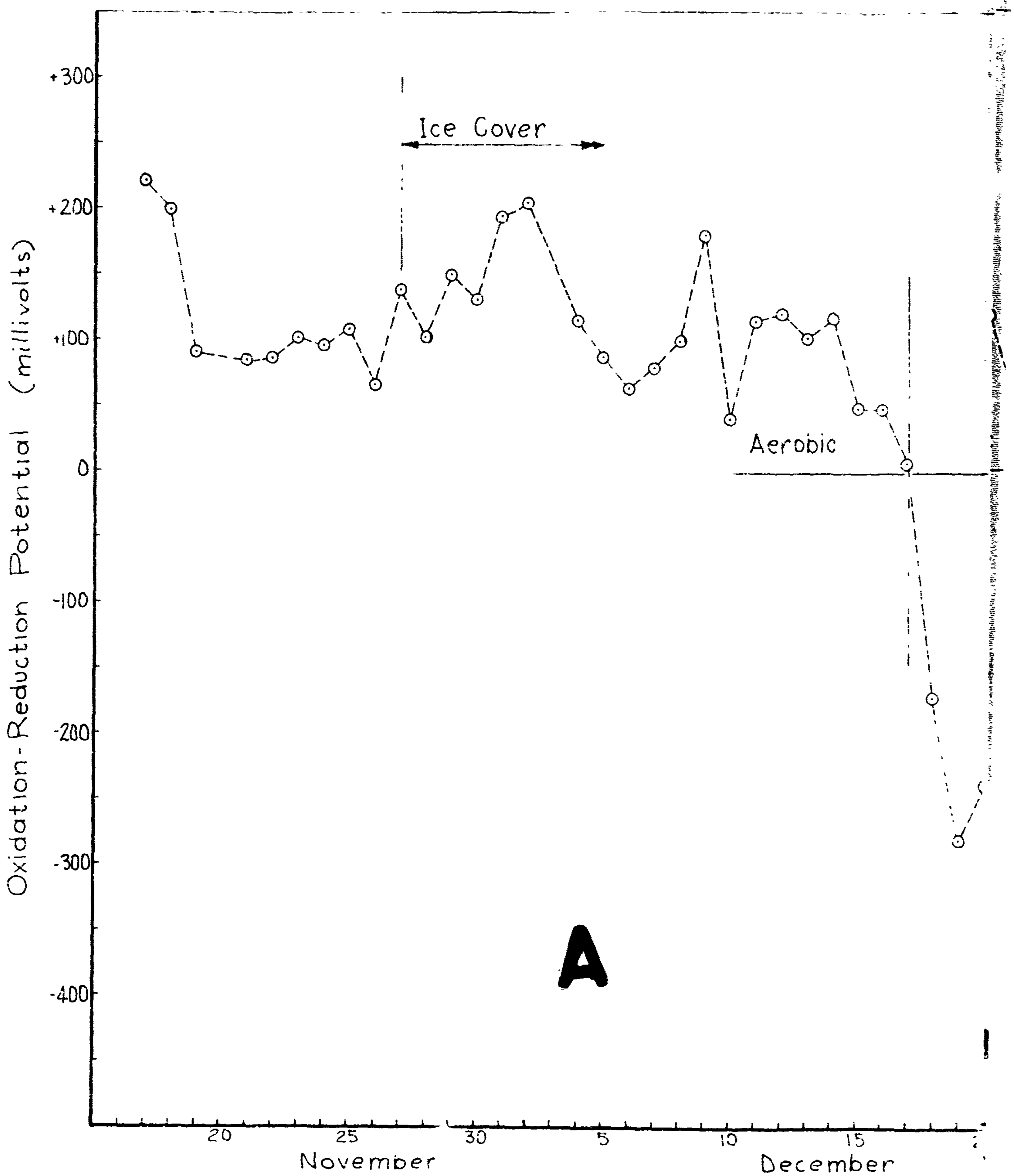
CHAPTER VI

DATA ANALYSIS

In general, it was stated in Chapter I that correlations of oxidation-reduction potential, pH and dissolved oxygen with air and water temperatures and solar radiation are to be made. For the data analysis, oxidation-reduction, pH and dissolved oxygen will be refered to as dependent variables; also, air and water temperatures and solar radiation will be refered to as independent variables.

In making these analyses it must be realized that all dependent variables are assumed to be the mean or representative of the daily variations. Realizing the possibility of error in obtaining these representative measurements, each measurement was averaged with the previous daily measurement to obtain more uniform data (this may or may not be indicative of the true situation). In addition the oxidation-reduction potential measurements were grouped into two categories, positive values only and all values. Thus, a total of eight dependent variables are provided. Figures 9, 10 and 11 are graphs showing the daily measurements of oxidation-reduction potential, pH and dissolved oxygen.

The independent variables, with the exception of the daily lagoon water temperatures, were also expanded. Not knowing what effect the previous daily air temperatures and solar radiation may have on the dependent variables, each daily measurement was averaged with the previous day, the two previous days and the three previous days. With correlations being made with air temperatures at the lagoons and at the university a



+300
+200
+100
0
-100
-200
-300
-400
Oxidation-Reduction Potential (millivolts)
Ice Cover
Aerobic
A
20
25
30
5
10
15
November
December

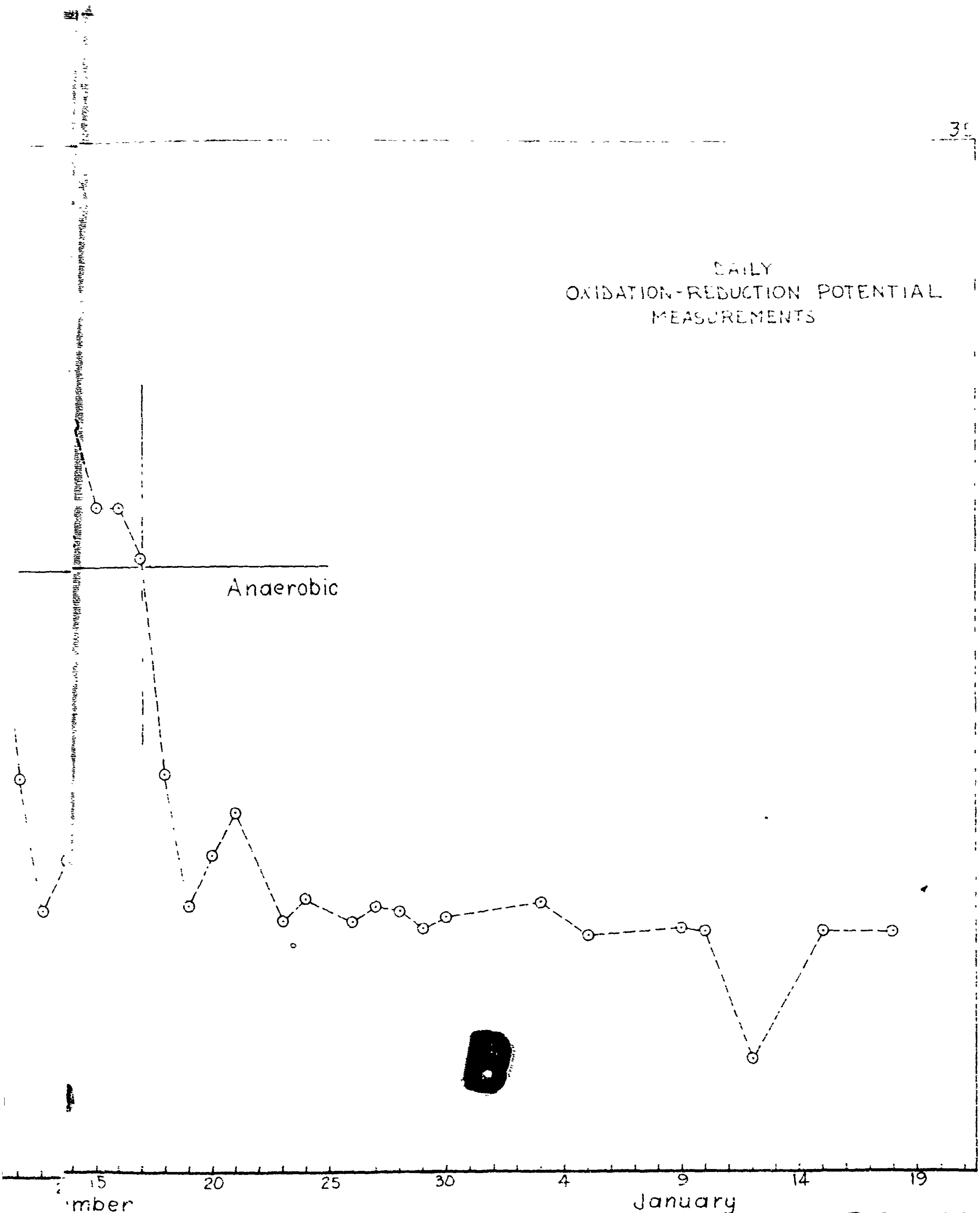
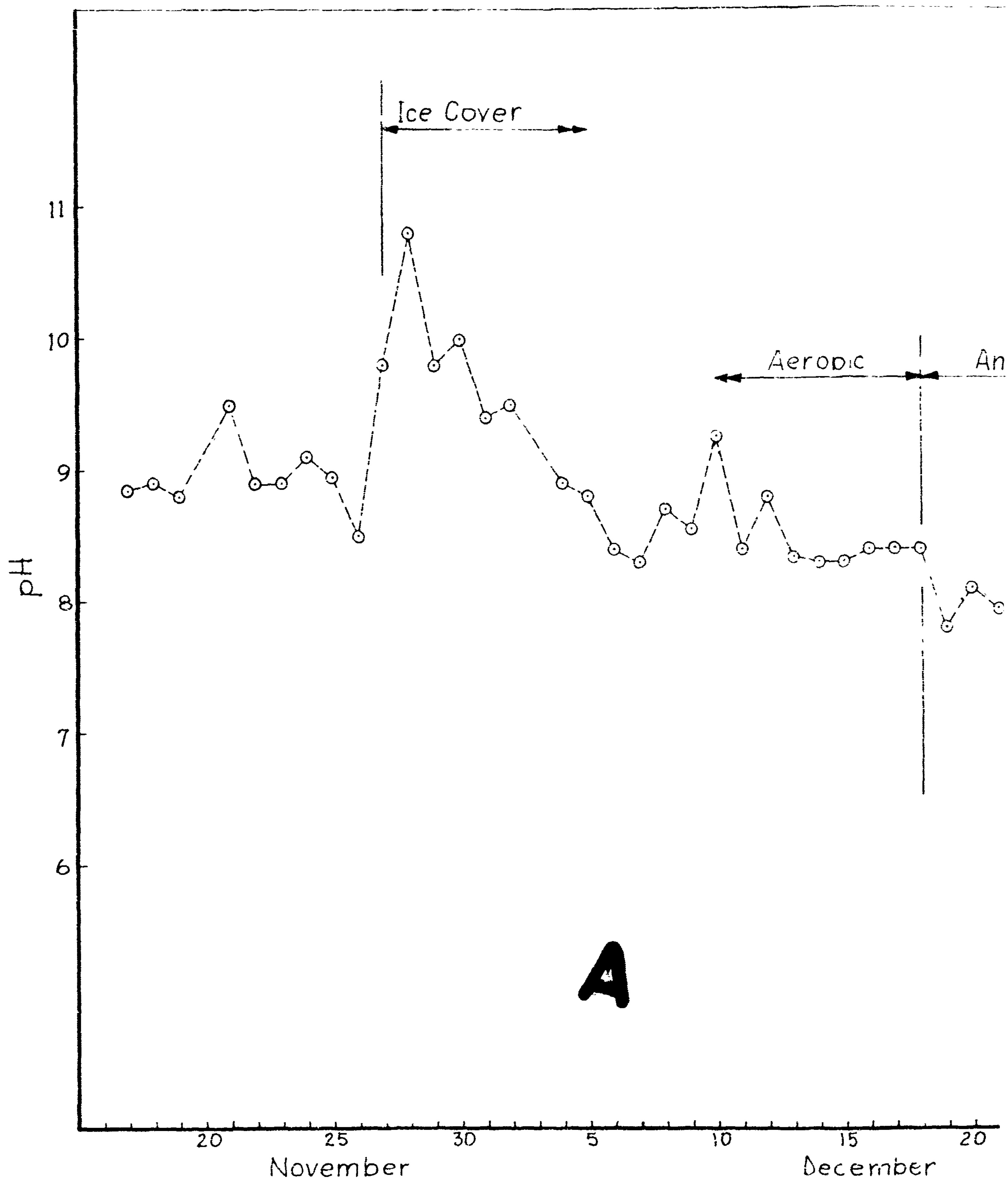

DAILY
OXIDATION-REDUCTION POTENTIAL
MEASUREMENTS
Anaerobic
15
20
25
30
4
9
14
19
mber
January

FIGURE 9.



Ice Cover
Aerobic
An
11
10
9
8
7
6
pH
20
25
30
5
10
15
20
November
December
A

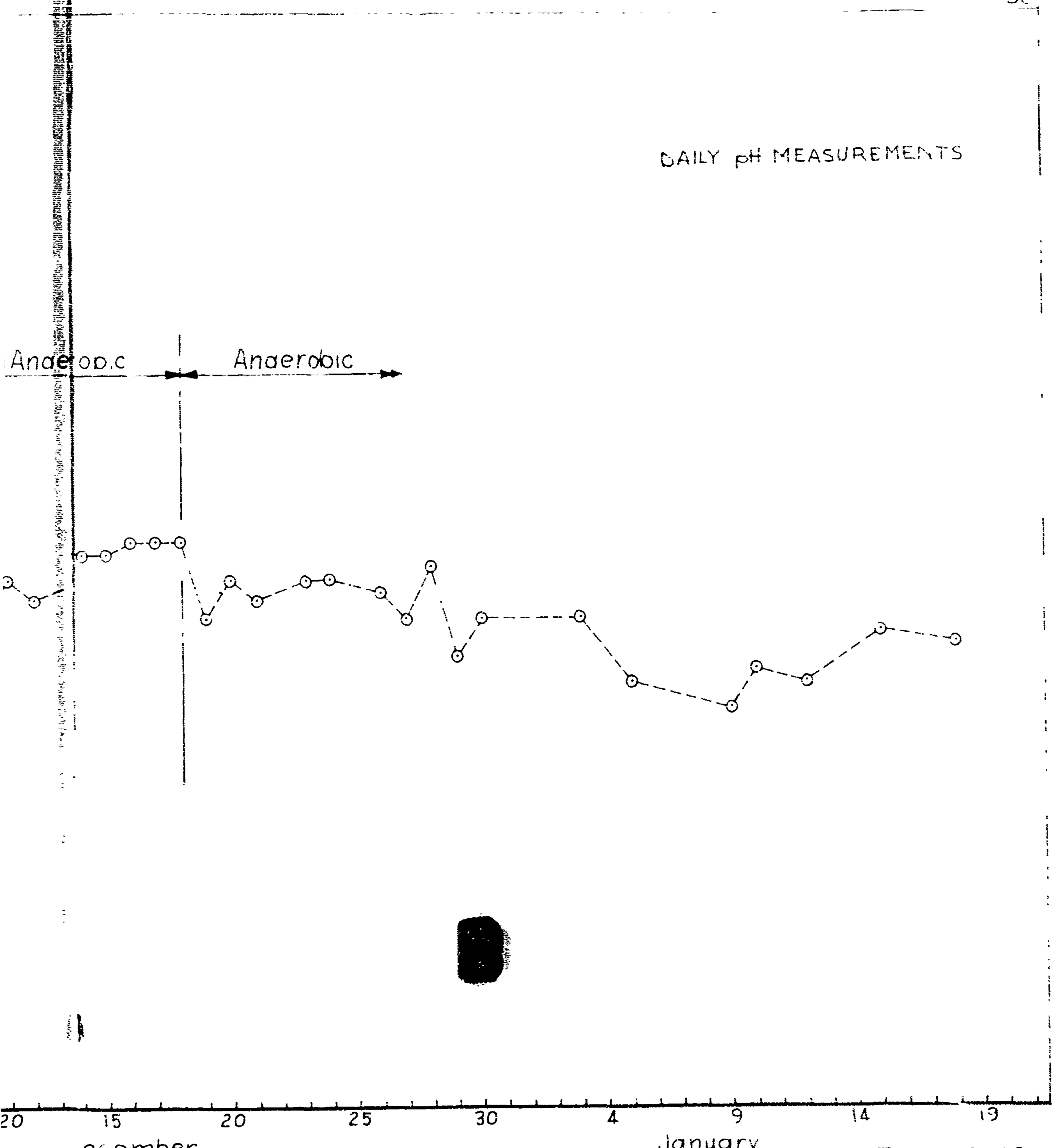
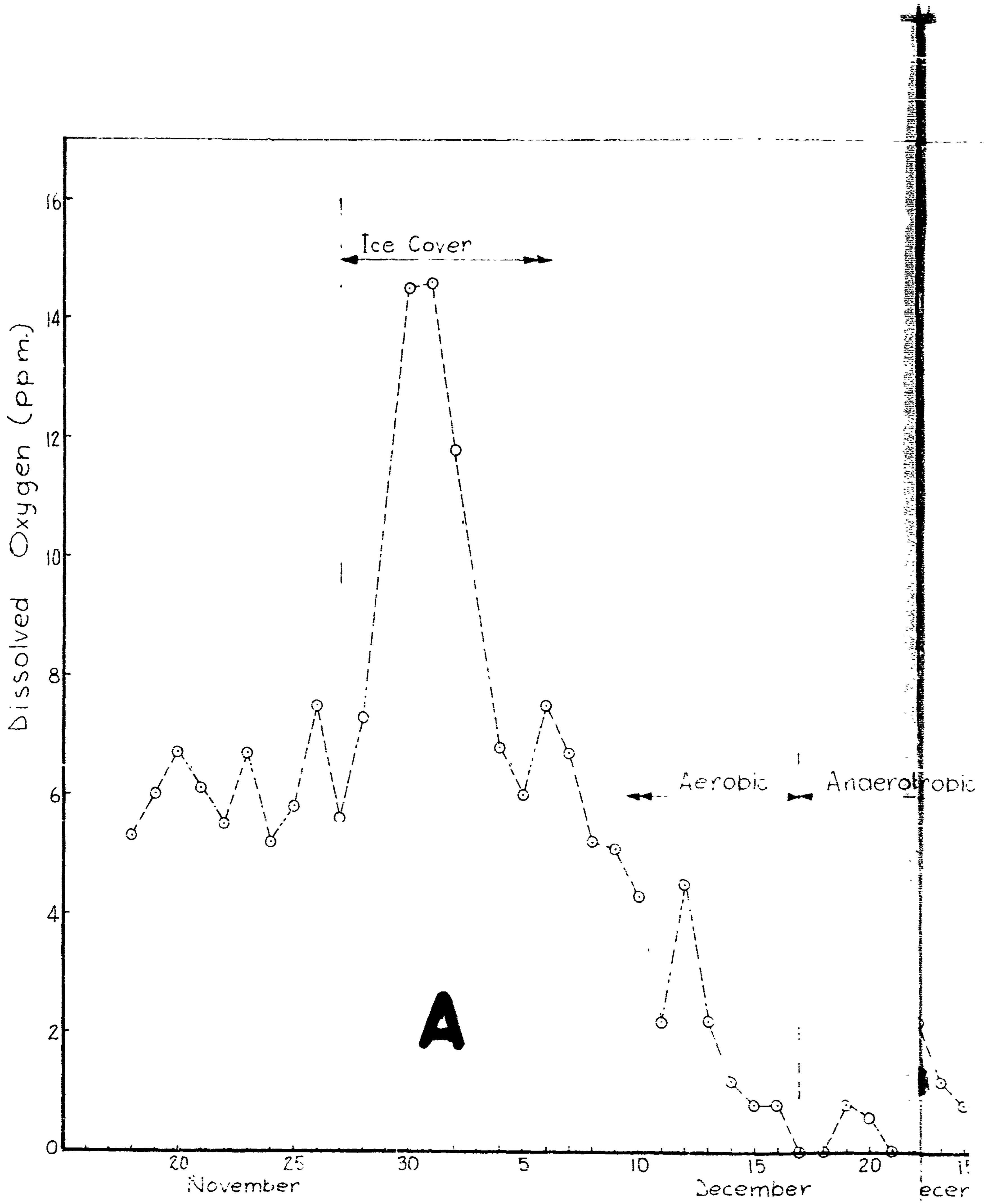

DAILY pH MEASUREMENTS
Anaerobic
Anaerobic
20
15
20
25
30
4
9
14
19
ecember
January

FIGURE 10.



Dissolved Oxygen (ppm.)
16
14
12
10
8
6
4
2
0
Ice Cover
Aerobic
Anaerobic
A
20
25
30
5
10
15
20
November
December

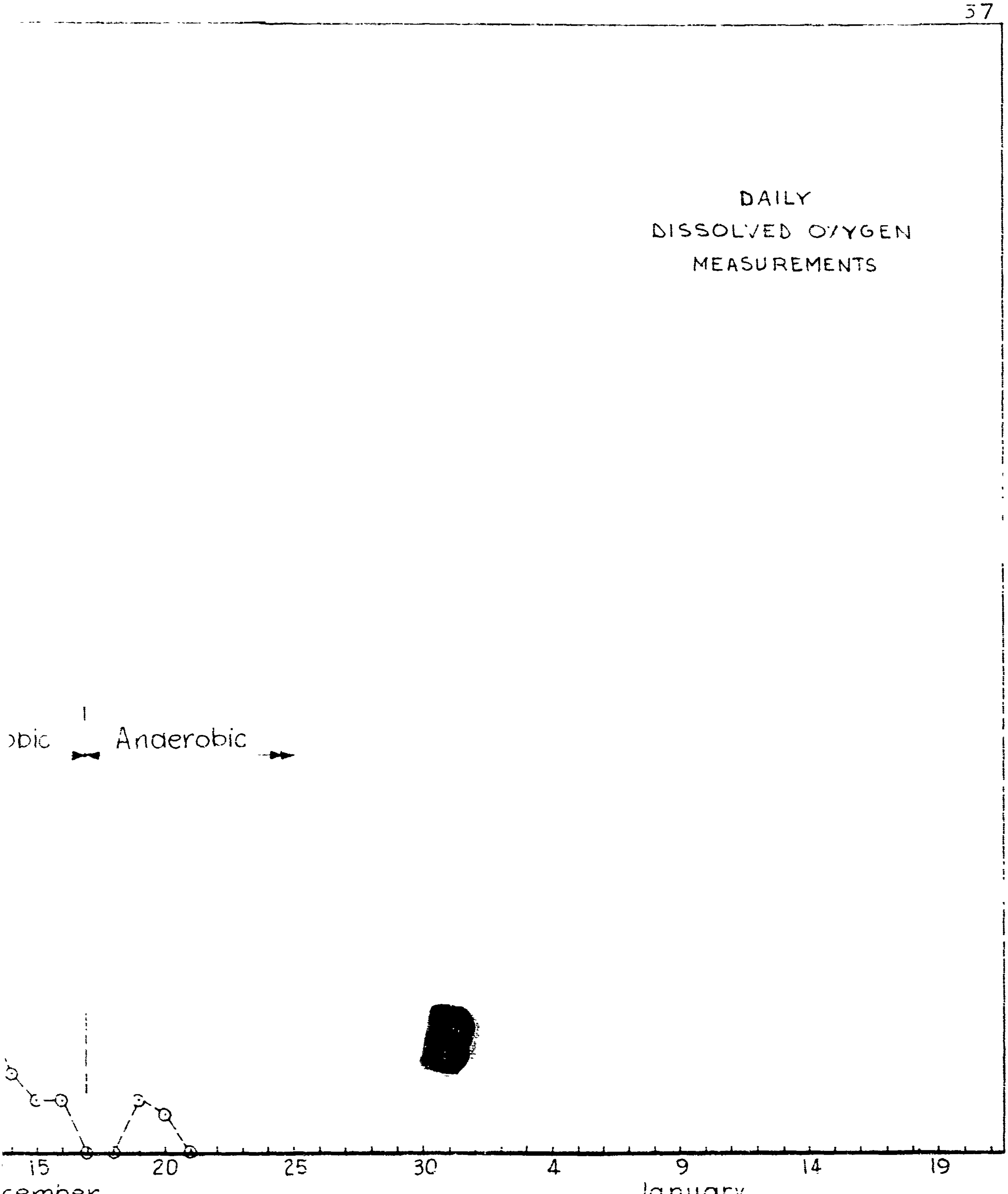

DAILY
DISSOLVED OXYGEN
MEASUREMENTS
obic
Anaerobic
15
20
25
30
4
9
14
19
cember
January

FIGURE 11.

a total of thirteen independent variables are provided. In all, 104 correlations are provided in this analysis.

Three statistical tools were employed in this analysis. The first was the method of least squares used to fit a curve to a set of data. The concept is to obtain an estimating or regression equation which will best fit the given data. This is accomplished by minimizing the sum of the squares of the vertical deviations about the appropriate curve. For simple linear regression or a straight line the equation takes the form $Y = b_o + b_1X$ where Y is the derived estimate of the dependent variable, b_o is the Y intercept, b_1 is the coefficient of the independent variable X that causes the change in the estimate Y for a given value of X.[18] Fig. 12 on page 78 is a graphical example.

The second tool is the correlation coefficient used to measure the degree of association between the dependent and independent variables. This coefficient is defined as

$$r = \frac{\sum xy}{(\sum x^2)(\sum y^2)} \quad . \tag{29}$$

When the degree of association is high, the value of r approaches unity and when the degree is low, this value approaches zero.[18]

The third tool is hypothesis testing. The "t" test is used to determine whether the previously determined correlation coefficient is representative of a true correlation; in other words, is the degree of association high enough to indicate whether any relationship exists between the two variables.[18]

These tools are time consuming and laborious unless a computer is utilized. The computer, a Philco 2000, has a package statistical program which was developed by the Air Force for biomedical space research and

which greatly simplifies the computations. With this program only four command cards are required, one to bring the statistical package into memory, the second to indicate the particular statistical method, the third to indicate the statistical parameters to be used and the fourth, a data card to start proce sing the individual values of the independent and dependent variables. The readout furnishes the regression equation plus all the estimates of the dependent variable for the given values of the independent variables. The value of the correlation coefficient is obtained by solving the above equation with the appropriate furnished data. The use of this computer in deriving a least squares equation greatly reduces the necessary calculations making an analysis of this magnitude practical and feasible.

The following Tables I through VIII tabulates each linear regression equation, correlation coefficient and the minimum correlation coefficient required to determine whether a relationship exists between the two variables in question.

TABLE I

LINEAR REGRESSION EQUATIONS AND CORRELATION COEFFICIENTS FOR DAILY OXIDATION-REDUCTION POTENTIAL (POSITIVE VALUES ONLY)

EQUATION	COEFFICIENT*
WITH DAILY RADIATION	
Y = 174.14 - .3544X	r = -.34
WITH TWO DAY RADIATION MEAN	
Y = 199.11 - .48255X	r = -.39
WITH THREE DAY RADIATION MEAN	
Y = 210.74 - .54225X	r = -.38
WITH FOUR DAY RADIATION MEAN	
Y = 213.57 - .56153X	r = -.35
WITH DAILY UNIVERSITY STATION AIR TEMPERATURES	
Y = 4.3073 + 3.1869X	r = .54
WITH TWO DAY MEAN UNIVERSITY STATION AIR TEMPERATURES	
Y = 1.2796 + 3.218X	r = .51
WITH THREE DAY MEAN UNIVERSITY STATION AIR TEMPERATURES	
Y = -2.6753 + 3.3200X	r = .50
WITH FOUR DAY MEAN UNIVERSITY STATION AIR TEMPERATURES	
Y = -22.495 + 3.8532	r = .54

*Minimum Required Correlation Coefficient = ±.36

TABLE I (CONT.)

EQUATION	COEFFICIENT
WITH DAILY LAGOON AIR TEMPERATURES	
$Y = -9.8241 + 3.6713X$	$r = .54$
WITH TWO DAY MEAN LAGOON AIR TEMPERATURES	
$Y = -13.882 + 3.7298X$	$r = .52$
WITH THREE DAY MEAN LAGOON AIR TEMPERATURES	
$Y = -26.874 + 4.0904X$	$r = .54$
WITH FOUR DAY MEAN LAGOON AIR TEMPERATURES	
$Y = -42.875 + 4.5338X$	$r = .55$
WITH DAILY LAGOON WATER TEMPERATURES	
$Y = 20.794 + 35.425X$	$r = .47$

TABLE II

LINEAR REGRESSION EQUATIONS AND CORRELATION COEFFICIENTS FOR TWO DAY MEAN OXIDATION-REDUCTION POTENTIAL (POSITIVE VALUES ONLY)

EQUATION	COEFFICIENT*
WITH DAILY RADIATION	
Y = 169.96 - .30334X	r = -.37
WITH TWO DAY RADIATION MEAN	
Y = 189.13 - .40225X	r = -.41
WITH THREE DAY RADIATION MEAN	
Y = 200.91 - .46247X	r = -.41
WITH FOUR DAY RADIATION MEAN	
Y = 207.36 - .49874X	r = -.39
WITH DAILY UNIVERSITY STATION AIR TEMPERATURES	
Y = 26.726 + 2.6573X	r = .57
WITH TWO DAY MEAN UNIVERSITY STATION AIR TEMPERATURES	
Y = 21.634 + 2.7655X	r = .56
WITH THREE DAY MEAN UNIVERSITY STATION AIR TEMPERATURES	
Y = 18.275 + 2.8528X	r = .55
WITH FOUR DAY MEAN UNIVERSITY STATION AIR TEMPERATURES	
Y = 6.8676 + 3.1349X	r = .56

*Minimum Required Correlation Coefficient = ±.36

TABLE II (CONT.)

EQUATION	COEFFICIENT
WITH DAILY LAGOON AIR TEMPERATURES	
Y = 9.6425 + 3.2376X	r = .60
WITH TWO DAY MEAN LAGOON AIR TEMPERATURES	
Y = 4.3851 + 3.3440X	r = .59
WITH THREE DAY MEAN LAGOON AIR TEMPERATURES	
Y = -3.9421 + 3.5605X	r = .59
WITH FOUR DAY MEAN LAGOON AIR TEMPERATURES	
Y = -12.795 + 3.7861X	r = .58
WITH DAILY LAGOON WATER TEMPERATURES	
Y = 29.770 + 34.810X	r = .605

TABLE III

LINEAR REGRESSION EQUATIONS AND CORRELATION COEFFICIENTS FOR DAILY OXIDATION-REDUCTION POTENTIAL (ALL VALUES)

EQUATION	COEFFICIENT*
WITH DAILY RADIATION	
Y = 77.846 - .55845X	r = -.18
WITH TWO DAY RADIATION MEAN	
Y = 161.10 - .95372X	r = -.27
WITH THREE DAY RADIATION MEAN	
Y = 252.02 - 1.3780X	r = -.34
WITH FOUR DAY RADIATION MEAN	
Y = 366.97 - 1.9198X	r = -.41
WITH DAILY UNIVERSITY STATION AIR TEMPERATURES	
Y = -176.84 + 4.604X	r = .24
WITH TWO DAY MEAN UNIVERSITY STATION AIR TEMPERATURES	
Y = -199.23 + 5.3187X	r = .27
WITH THREE DAY MEAN UNIVERSITY STATION AIR TEMPERATURES	
Y = -223.82 + 6.1665X	r = .30
WITH FOUR DAY MEAN UNIVERSITY STATION AIR TEMPERATURES	
Y = -287.90 + 8.2708X	r = .40

*Minimum Required Correlation Coefficient = ±.29

TABLE III (CONT.)

EQUATION	COEFFICIENT
WITH DAILY LAGOON AIR TEMPERATURES	
$Y = -193.79 + 5.1773X$	$r = .23$
WITH TWO DAY MEAN LAGOON AIR TEMPERATURES	
$Y = -217.53 + 5.9222X$	$r = .26$
WITH THREE DAY MEAN LAGOON AIR TEMPERATURES	
$Y = -254.75 + 7.1421X$	$r = .31$
WITH FOUR DAY MEAN LAGOON AIR TEMPERATURES	
$Y = -317.79 + 9.2521X$	$r = .38$
WITH DAILY LAGOON WATER TEMPERATURES	
$Y = -265.20 + 115.20X$	$r = .51$

TABLE IV

LINEAR REGRESSION EQUATIONS AND CORRELATION COEFFICIENTS FOR TWO DAY MEAN OXIDATION-REDUCTION POTENTIAL (ALL VALUES)

EQUATION	COEFFICIENT*
WITH DAILY RADIATION	
$Y = 83.102 - .55785X$	$r = -.18$
WITH TWO DAY RADIATION MEAN	
$Y = 160.20 - .92412X$	$r = -.26$
WITH THREE DAY RADIATION MEAN	
$Y = 249.10 - 1.339X$	$r = -.33$
WITH FOUR DAY RADIATION MEAN	
$Y = 368.16 - 1.900X$	$r = -.41$
WITH DAILY UNIVERSITY STATION AIR TEMPERATURES	
$Y = -155.33 + 4.0568X$	$r = .21$
WITH TWO DAY MEAN UNIVERSITY STATION AIR TEMPERATURES	
$Y = -179.41 + 4.833X$	$r = .25$
WITH THREE DAY MEAN UNIVERSITY STATION AIR TEMPERATURES	
$Y = -205.17 + 5.7187X$	$r = .29$
WITH FOUR DAY MEAN UNIVERSITY STATION AIR TEMPERATURES	
$Y = -265.25 + 7.6917X$	$r = .37$

*Minimum Required Correlation Coefficient = $\pm .29$

TABLE IV (CONT.)

EQUATION	COEFFICIENT
WITH DAILY LAGOON AIR TEMPERATURES	
Y = -174.45 + 4.7039X	r = .21
WITH TWO DAY MEAN LAGOON AIR TEMPERATURES	
Y = -198.86 + 5.4761X	r = .24
WITH THREE DAY MEAN LAGOON AIR TEMPERATURES	
Y = -234.62 + 6.6490X	r = .29
WITH FOUR DAY MEAN LAGOON AIR TEMPERATURES	
Y = -294.15 + 8.6416X	r = .36
WITH DAILY LAGOON WATER TEMPERATURES	
Y = -261.88 + 116.26X	r = .52

TABLE V

LINEAR REGRESSION EQUATIONS AND CORRELATION COEFFICIENTS FOR DAILY pH

EQUATION	COEFFICIENT*
WITH DAILY RADIATION	
$Y = 8.6291 - .00061X$	$r = -.05$
WITH TWO DAY RADIATION MEAN	
$Y = 8.6739 - .00082X$	$r = -.06$
WITH THREE DAY RADIATION MEAN	
$Y = 8.8156 - .00148X$	$r = -.09$
WITH FOUR DAY RADIATION MEAN	
$Y = 9.1294 - .00296X$	$r = -.16$
WITH DAILY UNIVERSITY STATION AIR TEMPERATURES	
$Y = 8.1784 + .01091X$	$r = .15$
WITH TWO DAY MEAN UNIVERSITY STATION AIR TEMPERATURES	
$Y = 8.2038 + .00996X$	$r = .13$
WITH THREE DAY MEAN UNIVERSITY STATION AIR TEMPERATURES	
$Y = 8.2008 + .010101X$	$r = .13$
WITH FOUR DAY MEAN UNIVERSITY STATION AIR TEMPERATURES	
$Y = 8.0072 + .016518X$	$r = .20$

*Minimum Required Correlation Coefficient = $\pm .29$

TABLE V (CONT.)

EQUATION	COEFFICIENT
WITH DAILY LAGOON AIR TEMPERATURES	
Y = 8.0604 + .014911X	r = .18
WITH TWO DAY MEAN LAGOON AIR TEMPERATURES	
Y = 8.0812 + .014065X	r = .16
WITH THREE DAY MEAN LAGOON AIR TEMPERATURES	
Y = 8.0327 + .015626X	r = .17
WITH FOUR DAY MEAN LAGOON AIR TEMPERATURES	
Y = 7.8503 + .02173X	r = .23
WITH DAILY LAGOON WATER TEMPERATURES	
Y = 7.9610 + .27415X	r = .31

TABLE VI

LINEAR REGRESSION EQUATIONS AND CORRELATION COEFFICIENTS FOR TWO DAY MEAN pH

EQUATION	COEFFICIENT*
WITH DAILY RADIATION	
$Y = 9.4363 - .005087X$	$r = -.23$
WITH TWO DAY RADIATION MEAN	
$Y = 9.8537 - .00708X$	$r = -.28$
WITH THREE DAY RADIATION MEAN	
$Y = 10.123 - .00832X$	$r = -.28$
WITH FOUR DAY RADIATION MEAN	
$Y = 10.020 - .00785X$	$r = -.07$
WITH DAILY UNIVERSITY STATION AIR TEMPERATURES	
$Y = 8.1288 + .01285X$	$r = .06$
WITH TWO DAY MEAN UNIVERSITY STATION AIR TEMPERATURES	
$Y = 7.4338 + .030902X$	$r = .22$
WITH THREE DAY MEAN UNIVERSITY STATION AIR TEMPERATURES	
$Y = 8.2002 + .01037X$	$r = .14$
WITH FOUR DAY MEAN UNIVERSITY STATION AIR TEMPERATURES	
$Y = 7.1732 + .03952X$	$r = .26$

*Minimum Required Correlation Coefficient = $\pm .29$

TABLE VI (CONT.)

EQUATION	COEFFICIENT
WITH DAILY LAGOON AIR TEMPERATURES	
$Y = 8.0307 + .01617X$	$r = .20$
WITH TWO DAY MEAN LAGOON AIR TEMPERATURES	
$Y = 8.0505 + .01534X$	$r = .18$
WITH THREE DAY MEAN LAGOON AIR TEMPERATURES	
$Y = 8.0262 + .016091X$	$r = .18$
WITH FOUR DAY MEAN LAGOON AIR TEMPERATURES	
$Y = 7.8930 + .02055X$	$r = .23$
WITH DAILY LAGOON WATER TEMPERATURES	
$Y = 7.9127 + .30256X$	$r = .35$

TABLE VII

LINEAR REGRESSION EQUATIONS AND CORRELATION COEFFICIENTS FOR DAILY DISSOLVED OXYGEN

EQUATION	COEFFICIENT*
WITH DAILY RADIATION	
Y = 7.3318 - .01027X	r = -.18
WITH TWO DAY RADIATION MEAN	
Y = 7.7854 - .012525X	r = -.19
WITH THREE DAY RADIATION MEAN	
Y = 7.4226 - .010881X	r = -.15
WITH FOUR DAY RADIATION MEAN	
Y = 6.7968 - .007965X	r = -.10
WITH DAILY UNIVERSITY STATION AIR TEMPERATURES	
Y = .00593 + .17350X	r = .55
WITH TWO DAY MEAN UNIVERSITY STATION AIR TEMPERATURES	
Y = -.38152 + .18401X	r = .57
WITH THREE DAY MEAN UNIVERSITY STATION AIR TEMPERATURES	
Y = -.33422 + .18216X	r = .55
WITH FOUR DAY MEAN UNIVERSITY STATION AIR TEMPERATURES	
Y = -.34429 + .17858X	r = .51

*Minimum Required Correlation Coefficient = $\pm$.35

TABLE VII (CONT.)

EQUATION	COEFFICIENT
WITH DAILY LAGOON AIR TEMPERATURES	
$Y = -.37967 + .18726X$	$r = .51$
WITH TWO DAY MEAN LAGOON AIR TEMPERATURES	
$Y = -.75747 + .19737X$	$r = .53$
WITH THREE DAY MEAN LAGOON AIR TEMPERATURES	
$Y = -1.1476 + .20822X$	$r = .53$
WITH FOUR DAY MEAN LAGOON AIR TEMPERATURES	
$Y = -1.3195 + .21124X$	$r = .52$
WITH DAILY LAGOON WATER TEMPERATURES	
$Y = 2.8034 + 1.0881X$	$r = .29$

TABLE VIII

LINEAR REGRESSION EQUATIONS AND CORRELATION COEFFICIENTS
FOR TWO DAY MEAN DISSOLVED OXYGEN

EQUATION	COEFFICIENT*
WITH DAILY RADIATION	
Y = 8.1185 - .013647X	r = -.27
WITH TWO DAY RADIATION MEAN	
Y = 8.3327 - .014795X	r = -.24
WITH THREE DAY RADIATION MEAN	
Y = 8.0216 - .013416X	r = -.20
WITH FOUR DAY RADIATION MEAN	
Y = 7.618 - .0116X	r = -.16
WITH DAILY UNIVERSITY STATION AIR TEMPERATURES	
Y = .11805 + .1717X	r = .60
WITH TWO DAY MEAN UNIVERSITY STATION AIR TEMPERATURES	
Y = -.32831 + .18458X	r = .63
WITH THREE DAY MEAN UNIVERSITY STATION AIR TEMPERATURES	
Y = -.33933 + .18466X	r = .61
WITH FOUR DAY MEAN UNIVERSITY STATION AIR TEMPERATURES	
Y = -.46551 + .18480X	r = .59

*Minimum Required Correlation Coefficient = $\pm$.35

TABLE VIII (CONT.)

EQUATION	COEFFICIENT
WITH DAILY LAGOON AIR TEMPERATURES	
Y = -.39465 + .19014X	r = .57
WITH TWO DAY MEAN LAGOON AIR TEMPERATURES	
Y = -.82077 + .20183X	r = .59
WITH THREE DAY MEAN LAGOON AIR TEMPERATURES	
Y = -1.1570 + .21086X	r = .60
WITH FOUR DAY MEAN LAGOON AIR TEMPERATURES	
Y = -1.3089 + .21319X	r = .59
WITH DAILY LAGOON WATER TEMPERATURES	
Y = 2.7209 + 1.1589X	r = .34

CHAPTER VII

DISCUSSION AND RECOMMENDATIONS

The data analysis indicates that there was a direct relationship between oxidation-reduction (ORP) and dissolved oxygen (DO) with air temperatures during aerobic conditions. In each correlation, whether one or two day ORP and DO measurements were used with lagoon or university air temperatures, all the coefficients were between .50 and .63. Also, in each of the two day mean ORP and DO correlations with air temperatures the coefficients were slightly higher than the daily ORP and DO correlations with air temperatures.

There was a direct relationship between ORP and water temperatures during both aerobic and anaerobic condition. Again the correlation between the two day mean ORP and water temperatures had a higher degree of association than between the daily ORP and water temperatures. This consistancy indicates that better correlations could result if continuous or dual measurements were taken.

The data analysis also shows that the degrees of association between pH and the independent variables were not high enough in any of the correlations to indicate any relationship. This was expected because pH is related to the chemical and biological activity rather than to the physical enviornment. In all correlations the coefficients were close to or lower than required by the test of hypothesis. It was observed, however, that the pH took a definite drop as did the ORP and DO when the stabilization

process went from aerobic to anaerobic. During the aerobic period the observed pH never went below 8.35 and during the anaerobic period the pH never went above 8.10; this indicates a less basic condition during anaerobic stabilization.

There also appears to be very little relationship between solar radiation and any of the dependent variables. In each correlation the coefficients were negative which indicates that high values of one associates with low values of the other. This seems to be in contrast with the common belief that an increase in light would increase the photosynthetic action rather than cause an apparent decrease. It is common belief that the light intensity during daylight hours at this altitude may approximate 5000 foot candles. This value is much higher than that required for maximum growth of oxygen producing algae (600 to 2000 foot candles).[19] This could account for the indirect relationship and also for the increase in ORP, pH and DO following freeze up of the lagoon surface; the ice possibly acting as a filter, thus reducing the light intensity, resulting in an increased growth of algae.

The data analysis did not show any large increases in the degree of association with the use of two, three and four day mean air temperatures and solar radiation. The general case, however, is a slight increase, but not enough to reccmmend continued research in this respect.

It is believed that ORP and DO can be a good indicator of aerobic stabilization requirements and that further study could be made towards utilizing these parameters in engineering control of the oxygen requirements to provide aerobic conditions on a year round basis. Continued research is recommended with respect to correlations of ORP with lagoon air and water temperatures and DO with lagoon air temperatures. To be

assured of accurate ORP measurements dual instrumentation is recommended. With the use of only one set of electrodes it is difficult to be certain that the measurements obtained are representative. It was stated in Chapter II that the platinum electrode could easily be poisoned and produce a memory effect. With two sets of electrodes one could be checked against the other.

For both ORP and DO, continuous measuring and recording is recommended. The WRRI Weather Station at the lagoon presently provides a continuous recording of air temperatures; with the Philco 2000 computer, and unlimited number of data pairs could be analyzed and correlated with ease.

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APPENDIX

TABLE IX

OXIDATION-REDUCTION POTENTIAL MEASUREMENT DATA

DATE	ORP (mv.)	DATE	ORP (mv.)	DATE	ORP (mv.)
Nov. 17	+222	Dec. 5	+ 87	Dec. 20	-240
18	+198	6	+ 63	21	-204
19	+ 90	7	+ 79	23	-294
21	+ 84	8	+ 99	24	-276
22	+ 87	9	+180	26	-294
23	+102	10	+ 39	27	-282
24	+ 96	11	+114	28	-285
25	+108	12	+120	29	-300
26	+ 66	13	+102	30	-291
27	+138	14	+117	Jan. 3	-279
28	+102	15	+ 48	5	-306
29	+150	16	+ 48	9	-300
30	+132	17	+ 6	10	-303
Dec. 1	+194	18	-174	12	-408
2	+204			15	-303
4	+114	19	-282	18	-303

TABLE X

TWO DAY MEAN OXIDATION-REDUCTION POTENTIALS

DATE	ORP (mv.)	DATE	ORP (mv.)	DATE	ORP (mv.)
Nov. 17	+222	Dec. 5	+100	Dec. 20	-261
18	+210	6	+ 75	21	-222
19	+144	7	+ 71	23	-249
21	+ 87	8	+ 89	24	-285
22	+ 86	9	+140	26	-285
23	+ 94	10	+110	27	-288
24	+ 99	11	+ 72	28	-284
25	+102	12	+117	29	-292
26	+ 87	13	+111	30	-295
27	+102	14	+110	Jan. 3	-279*
28	+120	15	+ 82	5	-306*
29	+126	16	+ 48	9	-300*
30	+141	17	+ 26	10	-303*
Dec. 1	+163	18	- 84	12	-408*
2	+199			15	-303*
4	+159	19	-227	18	-303*

*Considered to be the same as the daily measurement

TABLE XI

pH MEASUREMENT DATA

DATE	pH	DATE	pH	DATE	pH
Nov. 17	8.85	Dec. 5	8.80	Dec. 21	7.95
18	8.90	6	8.40	23	8.10
19	8.80	7	8.30	24	8.10
21	9.50	8	8.70	26	8.00
22	8.90	9	8.55	27	7.80
23	8.90	10	9.25	28	8.20
24	9.10	11	8.40	29	7.50
25	8.95	12	8.80	30	7.80
26	8.50	13	8.35	Jan. 3	7.80
27	9.80	14	8.30	5	7.30
28	10.80	15	8.30	9	7.10
29	9.80	16	8.40	10	7.40
30	10.00	17	8.40	12	7.30
Dec. 1	9.40	18	8.40	15	7.70
2	9.50	19	7.80	18	7.60
4	8.90	20	8.10		

TABLE XII

TWO DAY MEAN pH

DATE	pH	DATE	pH	DATE	pH
Nov. 17	8.85	Dec. 5	8.85	Dec. 21	8.02
18	8.88	6	8.60	23	8.[illegible]
19	8.85	7	8.35	24	8.10
21	9.15	8	8.50	26	8.05
22	9.20	9	8.62	27	7.90
23	8.90	10	8.90	28	8.00
24	9.00	11	8.82	29	7.85
25	9.02	12	8.60	30	7.65
26	8.72	13	8.57	Jan. 3	7.80*
27	9.15	14	8.32	5	7.30*
28	10.30	15	8.30	9	7.10*
29	10.30	16	8.35	10	7.25
30	9.90	17	8.40	12	7.30*
Dec. 1	9.70	18	8.40	15	7.70*
2	9.45	19	8.10	18	7.60*
4	9.20	20	7.95		

*Considered to be the same as the daily measurement

TABLE XIII

DISSOLVED OXYGEN MEASUREMENT DATA

DATE	DISSOLVED OXYGEN (ppm)	DATE	DISSOLVED OXYGEN (ppm)
Nov. 18	5.3	Dec. 5	6.0
19	6.0	6	7.5
20	6.7	7	6.7
21	6.1	8	5.2
22	5.5	9	5.1
23	6.7	10	4.3
24	5.2	11	2.2
25	5.8	12	4.5
26	7.5	13	2.2
27	5.6	14	1.2
28	7.3	15	0.8
29	1.6	16	0.8
30	14.5	17	0.0
Dec. 1	14.6	18	0.0
2	11.8	19	0.8
4	6.8	20	0.6

All Reading After Dec. 20 Were Zero

TABLE XIV

TWO DAY MEAN DISSOLVED OXYGEN

DATE	DISSOLVED OXYGEN (ppm)	DATE	DISSOLVED OXYGEN (ppm)
Nov. 18	5.30	Dec. 5	6.40
19	5.65	6	6.75
20	6.35	7	7.10
21	6.40	8	5.95
22	5.80	9	5.15
23	6.10	10	4.70
24	5.95	11	3.25
25	5.50	12	3.35
26	6.65	13	3.35
27	6.55	14	1.60
28	6.45	15	1.00
29	4.45	16	0.80
30	8.05	17	0.40
Dec. 1	14.55	18	0.00
2	13.20	19	0.40
4	9.30	20	0.70

All Reading After Dec. 20 Were Zero

TABLE XV

DIRECT & DIFFUSE SOLAR RADIATION
AT THE UNIVERSITY OF WYOMING STATION, LARAMIE, WYOMING
(In gm-cal/cm^2 of Horizontal Surface)

DATE	DAILY RADIATION	TWO DAY MEAN	THREE DAY MEAN	FOUR DAY MEAN
Nov. 1	312.6	-----	-----	-----
2	307.5	310.0	-----	-----
3	285.5	296.5	301.8	-----
4	278.6	282.0	290.5	296.0
5	231.5	255.0	265.2	275.8
6	226.2	228.8	245.4	255.4
7	264.5	245.4	240.7	250.2
8	287.7	276.1	259.5	252.5
9	204.6	246.2	252.3	245.8
10	172.7	188.6	221.7	232.4
11	197.6	185.2	191.6	215.6
12	117.8	147.7	162.7	173.2
13	163.3	140.6	159.6	162.8
14	120.2	141.8	133.8	149.7
15	201.2	160.7	161.6	150.6
16	103.1	152.2	141.5	147.0
17	93.2	98.2	132.5	129.4
18	151.9	122.0	116.1	137.4
19	186.9	169.4	144.0	133.8
20	155.6	171.3	164.8	146.9
21	212.8	184.2	185.1	176.8

TABLE XV (CONT.)

DATE	DAILY RADIATION	TWO DAY MEAN	THREE DAY MEAN	FOUR DAY MEAN
Nov. 22	281.1	246.9	216.3	209.1
23	144.4	212.8	212.8	198.5
24	156.7	150.5	194.1	198.8
25	69.3	113.0	123.5	162.9
26	290.6	180.0	172.2	165.5
27	285.7	288.2	215.2	200.6
28	288.3	287.0	288.2	233.5
29	267.3	277.8	280.4	283.0
30	253.4	260.4	269.7	273.7
Dec. 1	177.9	215.7	232.9	246.7
2	224.2	201.0	218.5	230.7
3	257.0	240.6	219.7	228.1
4	173.7	215.4	218.3	208.2
5	228.2	200.9	219.6	220.8
6	208.8	218.5	203.6	216.9
7	160.1	184.4	199.0	192.7
8	155.8	157.9	174.9	188.2
9	211.4	183.6	175.8	184.0
10	83.5	147.5	150.2	152.7
11	81.8	82.6	125.6	133.1
12	279.1	180.5	148.1	164.0
13	203.8	241.4	188.2	162.0
14	228.2	216.0	237.0	198.2

TABLE XV (CONT.)

DATE	DAILY RADIATION	TWO DAY MEAN	THREE DAY MEAN	FOUR DAY MEAN
Dec. 15	261.1	244.6	231.0	243.5
16	288.8	275.0	259.4	245.5
17	277.3	283.0	275.8	263.8
18	306.9	292.1	291.1	283.6
19	242.7	[illegible]	275.7	279.0
20	250.5	246.6	266.8	269.4
21	247.9	249.2	247.1	262.0
22	140.1	194.0	212.9	220.4
23	96.7	118.4	161.6	183.8
24	292.1	194.4	173.4	194.2
25	249.4	270.8	212.8	194.6
26	201.5	225.4	247.7	210.0
27	249.0	225.3	233.4	248.0
28	148.0	198.5	199.6	212.0
29	195.6	171.8	197.6	198.6
30	170.3	183.0	171.4	190.8
31	277.0	223.6	214.4	197.8
Jan. 1	195.5	236.2	214.3	209.6
2	279.7	237.6	250.7	230.6
3	255.1	267.4	243.4	251.8
4	243.3	249.2	259.4	243.4
5	235.2	239.2	244.5	253.3
6	136.8	186.0	205.1	217.6

TABLE XV (CONT.)

DATE	DAILY RADIATION	TWO DAY MEAN	THREE DAY MEAN	FOUR DAY MEAN
Jan. 7	253.1	200.0	208.4	217.1
8	242.5	247.8	210.8	216.9
9	279.3	260.9	258.3	227.9
10	190.3	234.8	237.4	241.3
11	273.4	231.8	247.7	246.4
12	251.7	262.6	238.5	248.7
13	269.5	260.6	264.9	246.2
14	159.4	214.4	226.9	238.5
15	149.0	154.2	192.6	207.4
16	282.2	215.6	196.9	215.0
17	332.9	307.6	254.7	230.3
18	328.8	330.8	314.6	273.2
19	178.9	253.8	280.2	280.7
20	200.5	189.7	236.1	260.3
21	375.6	288.0	251.7	271.0
22	245.7	310.6	273.9	250.2
23	259.2	252.4	293.5	270.2
24	252.8	256.0	252.6	283.3
25	349.4	301.1	287.1	276.8
26	314.7	332.0	305.6	294.0
27	309.1	311.9	324.4	306.5
28	293.7	301.4	305.8	316.7
29	188.1	240.9	263.6	276.4

TABLE XVI

DAILY AIR TEMPERATURES
AT THE UNIVERSITY OF WYOMING STATION, LARAMIE, WYOMING

DATE	MAX. TEMP. °F	MIN. TEMP. °F	MEAN TEMP. °F	DATE	MAX. TEMP. °F	MIN. TEMP. °F	MEAN TEMP. °F
Nov. 1	65	32	48.5	Nov. 23	49	32	40.5
2	60	35	47.5	24	47	33	40.0
3	56	28	42.0	25	44	26	35.0
4	60	30	45.0	26	28	17	22.5
5	58	36	47.0	27	30	17	23.5
6	57	28	42.5	28	31	15	23.0
7	56	29	42.5	29	41	14	27.5
8	58	23	40.5	30	49	21	35.0
9	52	31	41.5	Dec. 1	40	25	32.5
10	52	27	39.5	2	46	20	33.0
11	46	28	37.0	3	51	31	41.0
12	44	26	25.0	4	55	30	42.5
13	47	30	38.5	5	56	36	46.0
14	52	33	42.5	6	57	29	43.0
15	48	37	42.5	7	52	27	39.5
16	47	35	41.0	8	53	29	41.0
17	49	35	42.0	9	51	23	37.0
18	51	37	44.0	10	41	23	32.0
19	47	35	41.0	11	35	30	32.5
20	41	30	35.5	12	37	13	25.0
21	37	26	31.5	13	34	13	23.5
22	45	20	32.5	14	21	7	14.0

TABLE XVI (CONT.)

DATE	MAX. TEMP. °F	MIN. TEMP. °F	MEAN TEMP. °F
Dec. 15	15	-6	4.5
16	17	-9	4.0
17	25	0	12.5
18	19	-9	5.0
19	34	14	24.0
20	39	18	28.5
21	47	19	33.0
22	44	23	33.5
23	30	14	22.0
24	36	2	19.0
25	43	20	31.5
26	34	15	24.5
27	43	8	25.5
28	47	30	38.5
29	52	21	36.5
30	45	25	35.0
31	33	16	24.5
Jan. 1	25	12	18.5
2	23	4	13.5
3	33	14	23.5
4	42	21	31.5
5	42	29	35.5
6	45	29	37.0
7	44	31	37.5
Jan. 8	54	33	43.5
9	39	24	31.5
10	44	22	33.0
11	41	28	34.5
12	30	17	23.5
13	35	14	24.5
14	38	24	31.0
15	28	15	21.5
16	19	2	10.5
17	21	1	11.0
18	40	9	24.5
19	22	2	12.0
20	15	-3	6.0
21	20	-14	3.0
22	25	-2	11.5
23	24	8	16.0
24	25	5	15.0
25	23	-2	10.5
26	35	9	22.0
27	40	22	31.0
28	35	10	22.5
29	40	15	27.5
30	45	23	34.0
31	34	19	26.5

TABLE XVII

RUNNING MEAN DAILY AIR TEMPERATURES
AT THE UNIVERSITY OF WYOMING STATION, LARAMIE, WYOMING

DATE	TWO DAY MEAN °F	THREE DAY MEAN °F	FOUR DAY MEAN °F
Nov. 2	48.00	-----	-----
3	44.25	46.00	-----
4	43.50	47.16	45.75
5	46.00	47.00	45.38
6	44.75	47.16	44.12
7	42.50	46.00	44.25
8	41.50	41.83	43.12
9	41.00	41.50	41.75
10	40.50	40.50	41.00
11	38.25	36.00	39.62
12	36.00	33.83	38.25
13	36.75	36.83	37.50
14	40.50	38.67	38.25
15	42.50	41.16	39.62
16	41.75	41.33	41.12
17	41.50	41.50	42.00
18	43.00	42.67	42.38
19	42.50	42.67	42.00
20	38.25	40.16	40.62
21	33.50	35.67	38.00
22	32.00	33.16	35.12
23	36.50	34.83	35.00

DATE	TWO DAY MEAN °F	THREE DAY MEAN °F	FOUR DAY MEAN °F
Nov. 24	40.25	37.67	36.12
25	37.50	38.50	37.00
26	28.75	32.83	34.50
27	23.00	27.00	30.25
28	23.25	22.67	26.00
29	25.25	21.33	24.12
30	31.25	28.50	27.25
Dec. 1	33.75	30.00	29.50
2	32.75	33.50	32.00
3	37.00	35.50	35.38
4	41.72	38.83	37.25
5	44.25	43.17	40.62
6	44.50	43.83	43.12
7	41.25	42.83	42.75
8	40.25	41.16	42.38
9	39.00	35.83	40.12
10	34.50	36.67	37.38
11	32.25	33.83	35.62
12	28.75	29.50	31.62
13	24.25	27.00	28.25
14	18.75	21.17	23.75
15	9.50	14.00	16.75

TABLE XVII (CONT.)

DATE	TWO DAY MEAN °F	THREE DAY MEAN °F	FOUR DAY MEAN °F
Dec. 16	4.25	7.50	11.50
17	8.25	7.33	8.75
18	8.75	7.17	6.50
19	14.50	13.83	11.38
20	26.25	19.16	17.50
21	30.75	23.50	22.62
22	33.25	31.67	29.75
23	27.75	29.50	29.25
24	21.50	27.16	26.88
25	25.25	24.16	26.50
26	26.00	21.67	24.25
27	25.00	27.16	25.12
28	32.00	29.50	30.00
29	37.50	33.50	31.25
30	35.75	36.33	33.88
31	24.75	32.00	33.62
Jan. 1	21.50	26.00	28.25
2	16.00	18.83	22.88
3	18.50	18.50	20.00
4	27.50	22.83	21.88
5	33.50	30.16	26.00
6	36.25	34.67	31.88
7	37.25	37.67	35.38
Jan. 8	40.00	39.30	38.38
9	37.50	37.50	37.38
10	32.25	36.00	36.38
11	33.75	33.00	35.62
12	29.00	30.33	30.62
13	24.00	27.53	28.88
14	27.25	26.30	28.38
15	26.25	25.67	25.12
16	16.00	21.00	21.88
17	10.75	14.33	18.50
18	17.75	15.33	16.88
19	18.25	15.83	14.50
20	9.00	14.17	13.38
21	4.50	7.00	11.38
22	7.25	6.83	8.12
23	14.25	10.16	9.12
24	15.50	14.16	11.38
25	13.25	13.83	13.25
26	16.25	15.83	15.88
27	26.50	21.17	19.62
28	27.25	25.17	21.50
29	25.00	27.00	25.75
30	30.75	28.00	28.75

TABLE XVIII

DAILY AIR TEMPERATURES
AT THE CITY STABILIZATION LAGOONS, LARAMIE, WYOMING

DATE	MAX. TEMP. °F	MIN. TEMP. °F	MEAN TEMP. °F
Nov. 1	66	26	46.0
2	59	27	43.00
3	57	26	41.5
4	58	24	41.0
5	59	27	43.0
6	58	24	41.0
7	58	26	42.0
8	58	18	38.0
9	51	25	38.0
10	51	24	37.5
11	45	24	34.5
12	42	29	35.5
13	44	30	37.0
14	52	29	40.5
15	50	34	42.0
16	47	37	42.0
17	51	36	43.5
18	50	38	44.0
19	46	36	41.0
20	42	26	34.0
21	38	25	31.5
22	38	30	34.0
Nov. 23	48	32	40.0
24	49	34	41.5
25	44	24	34.0
26	28	22	25.0
27	30	24	27.0
28	32	24	28.0
29	42	14	28.0
30	48	17	32.5
Dec. 1	42	14	28.5
2	45	14	29.5
3	49	30	39.5
4	54	36	45.0
5	54	23	38.5
6	56	19	37.5
7	51	20	35.5
8	52	23	37.5
9	53	20	36.5
10	41	23	32.0
11	34	22	28.0
12	35	12	23.5
13	32	18	25.0
14	21*	10**	15.5

TABLE XVIII (CONT.)

DATE	MAX. TEMP. °F	MIN. TEMP. °F	MEAN TEMP. °F	DATE	MAX. TEMP. °F	MIN. TEMP. °F	MEAN TEMP. °F
Dec. 15	15*	1**	8.0	Jan. 5	42	29	35.5
16	17*	-2**	7.5	6	45	30	37.5
17	25*	5**	15.0	7	43	32	37.5
18	19*	-2**	8.5	8	54	34	44.0
19	34*	16**	25.0	9	40	20	30.0
20	39*	18**	28.5	10	40	31	35.5
21	47*	19**	33.0	11	41*	26**	33.5
22	44*	22**	33.0	12	30*	18**	24.0
23	30*	16**	23.0	13	35*	16**	25.5
24	36*	7**	21.5	14	38*	23**	30.5
25	43*	20**	31.5	15	28*	16**	22.0
26	34*	16**	25.0	16	19*	7**	13.0
27	43*	11**	27.0	17	21*	6**	13.5
28	47*	28**	37.5	18	40*	12**	26.0
29	51	22**	36.5	19	22*	7**	14.5
30	46	20	28.0	20	15*	3**	9.0
31	34	17	25.5	21	20*	-5**	7.5
Jan. 1	26	7	16.5	22	25*	3**	14.0
2	25	6	15.5	23	24*	11**	17.5
3	34	18	26.0	24	25*	9**	17.0
4	42	23	32.5	25	23*	3**	13.0

*Same as University of Wyoming Station Temperatures
**From correlation equation Y = 5 + .75X (Figure 12)

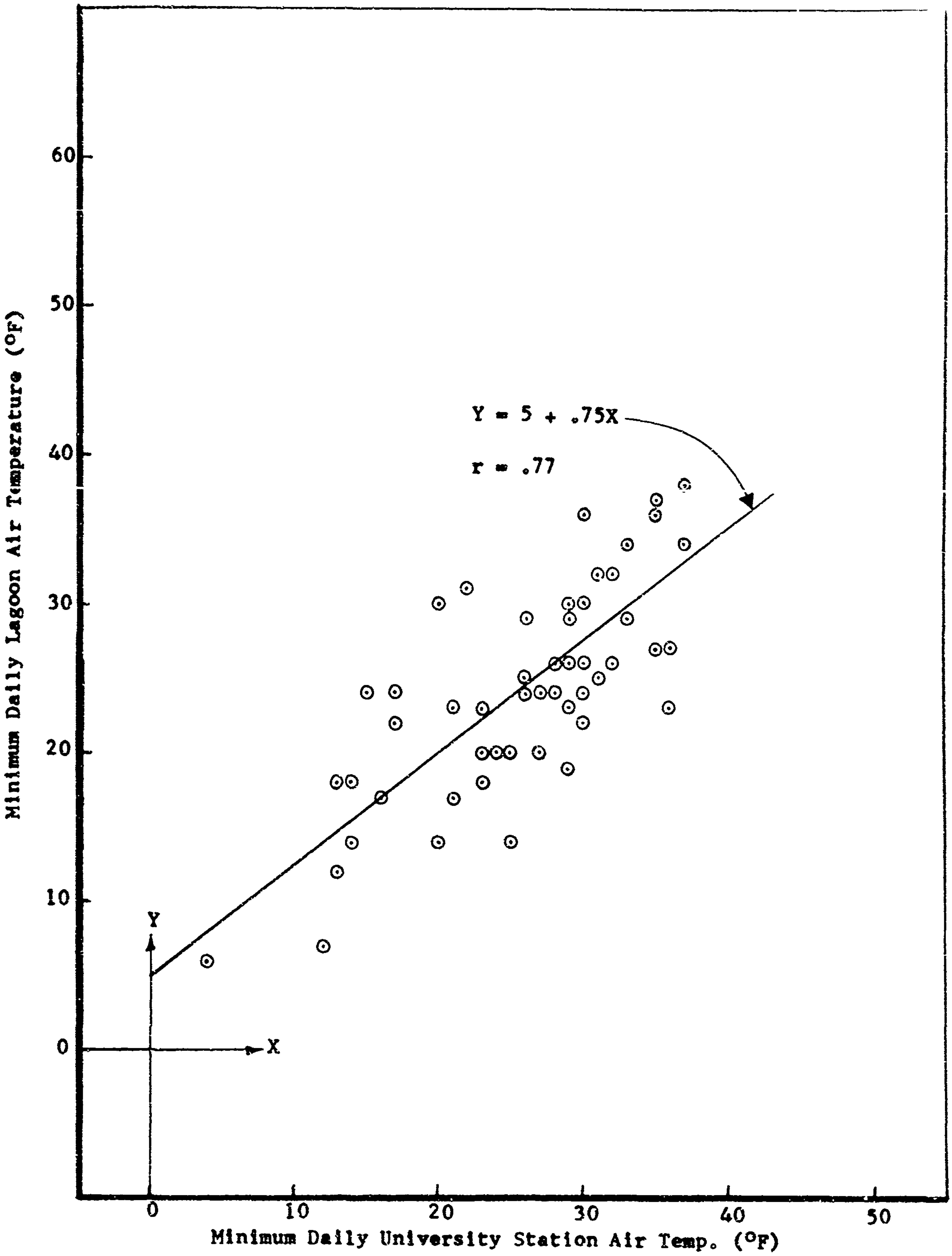

Y = 5 + .75X
r = .77
Minimum Daily Lagoon Air Temperature (°F)
60
50
40
30
20
10
0
Y
X
0
10
20
30
40
50
Minimum Daily University Station Air Temp. (°F)

FIGURE 12.

TABLE XIX

RUNNING MEAN DAILY AIR TEMPERATURES
AT THE CITY STABILIZATION LAGOONS, LARAMIE, WYOMING

DATE	TWO DAY MEAN °F	THREE DAY MEAN °F	FOUR DAY MEAN °F
Nov. 2	44.5	----	----
3	42.2	43.5	----
4	41.2	41.8	42.9
5	42.0	41.8	42.1
6	42.0	41.7	41.6
7	41.5	42.0	41.8
8	40.0	40.3	41.0
9	38.0	39.3	39.8
10	37.8	37.8	38.9
11	36.0	36.7	37.0
12	35.0	35.8	36.4
13	36.2	35.7	36.2
14	38.8	37.7	36.9
15	41.2	39.8	38.8
16	42.0	41.5	40.4
17	42.8	42.5	42.0
18	43.8	43.2	42.9
19	42.5	42.8	42.6
20	37.5	39.7	40.6
21	32.8	35.5	37.6
22	32.8	33.2	35.1

DATE	TWO DAY MEAN °F	THREE DAY MEAN °F	FOUR DAY MEAN °F
23	37.0	35.2	34.9
Nov. 24	40.8	38.5	36.8
25	37.8	38.5	37.4
26	29.5	33.5	35.1
27	26.0	28.7	31.9
28	27.5	26.7	28.5
29	28.0	27.7	27.0
30	30.2	29.5	28.9
Dec. 1	30.5	29.7	29.2
2	29.0	30.2	29.6
3	34.5	32.5	32.5
4	42.2	38.0	35.6
5	41.8	41.0	38.1
6	38.0	40.3	40.1
7	36.5	37.2	39.1
8	36.5	36.8	37.2
9	37.0	36.5	36.8
10	34.2	35.3	35.4
11	30.0	32.2	33.5
12	25.8	27.8	30.0
13	24.2	25.5	27.1

TABLE XIX (CONT.)

DATE	TWO DAY MEAN °F	THREE DAY MEAN °F	FOUR DAY MEAN °F
14	20.2	21.3	23.0
15	11.8	16.2	18.0
16	7.8	10.3	14.0
17.	11.2	10.2	11.5
18	11.8	10.3	9.8
19	16.8	16.2	14.0
20	26.8	20.7	19.2
21	30.8	28.8	23.8
22	33.0	31.5	29.9
23	28.0	29.7	29.4
24	22.2	25.8	27.6
25	26.5	25.3	27.2
26	28.2	26.0	25.2
27	26.0	27.8	26.7
28	32.2	29.8	30.2
29	37.0	33.7	31.5
30	32.2	34.0	32.2
31	26.8	30.0	31.9
Jan. 1	21.0	23.3	26.6
2	16.0	19.2	21.4
3	20.8	19.3	20.9
4	29.2	24.7	22.6
Jan. 5	34.0	31.3	27.4
6	36.5	35.2	32.9
7	37.5	36.8	35.8
8	40.8	39.7	38.6
9	37.0	37.2	37.2
10	32.8	36.5	36.8
11	34.5	33.0	35.8
12	28.8	31.0	30.8
13	24.8	27.7	29.6
14	28.0	26.7	28.4
15	26.2	26.0	25.5
16	17.5	21.8	22.8
17	13.2	16.2	19.8
18	19.8	17.5	18.6
19	20.2	18.0	16.8
20	11.8	16.5	15.8
21	8.2	10.3	14.2
22	10.8	10.2	11.2
23	15.8	13.0	12.0
24	17.2	16.2	14.0
25	15.0	15.8	15.4

TABLE XIX (CONT.)

DATE	TWO DAY MEAN °F	THREE DAY MEAN °F	FOUR DAY MEAN °F
14	20.2	21.3	23.0
15	11.8	16.2	18.0
16	7.8	10.3	14.0
17.	11.2	10.2	11.5
18	11.8	10.3	9.8
19	16.8	16.2	14.0
20	26.8	20.7	19.2
21	30.8	28.8	23.8
22	33.0	31.5	29.9
23	28.0	29.7	29.4
24	22.2	25.8	27.6
25	26.5	25.3	27.2
26	28.2	26.0	25.2
27	26.0	27.8	26.7
28	32.2	29.8	30.2
29	37.0	33.7	31.5
30	32.2	34.0	32.2
31	26.8	30.0	31.9
Jan. 1	21.0	23.3	26.6
2	16.0	19.2	21.4
3	20.8	19.3	20.9
4	29.2	24.7	22.6
Jan. 5	34.0	31.3	27.4
6	36.5	35.2	32.9
7	37.5	36.8	35.8
8	40.8	39.7	33.6
9	37.0	37.2	37.2
10	32.8	36.5	36.8
11	34.5	33.0	35.8
12	28.8	31.0	30.8
13	24.8	27.7	29.6
14	28.0	26.7	28.4
15	26.2	26.0	25.5
16	17.5	21.8	22.8
17	13.2	16.2	19.8
18	19.8	17.5	18.6
19	20.2	18.0	16.8
20	11.8	16.5	15.8
21	8.2	10.3	14.2
22	10.8	10.2	11.2
23	15.8	13.0	12.0
24	17.2	16.2	14.0
25	15.0	15.8	15.4

TABLE XX

DAILY LAGOON WATER TEMPERATURES, °C

DATE	TEMP.	DATE	TEMP.	DATE	TEMP.
Nov. 17	4.0	Dec. 4	3.0	Dec. 20	1.4
18	4.0	5	2.4	21	1.4
19	4.0	6	2.4	23	1.3
20	4.0	7	2.5	24	2.0
21	2.0	8	2.6	26	1.7
22	1.5	9	2.8	27	1.3
23	2.5	10	3.0	28	1.6
24	2.5	11	2.8	29	1.4
25	2.8	12	2.4	30	1.4
26	0.5	13	2.5	Jan. 3	1.7
27	0.0	14	1.8	5	1.8
28	1.0	15	1.8	9	1.5
29	1.5	16	1.2	10	0.9
30	2.0	17	0.7	12	1.5
Dec. 1	2.3	18	1.0	15	1.8
2	3.0	19	1.2	18	1.0

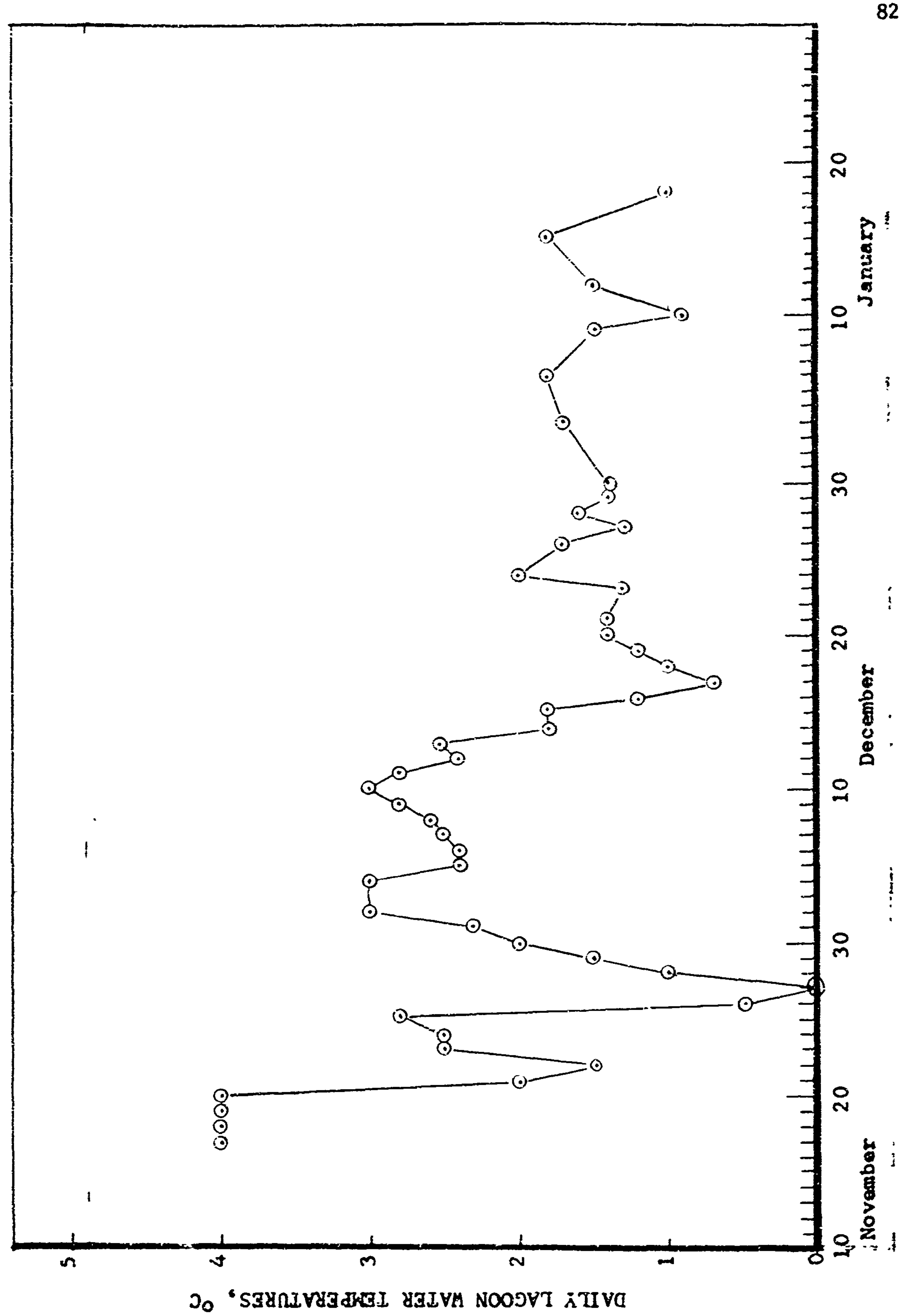
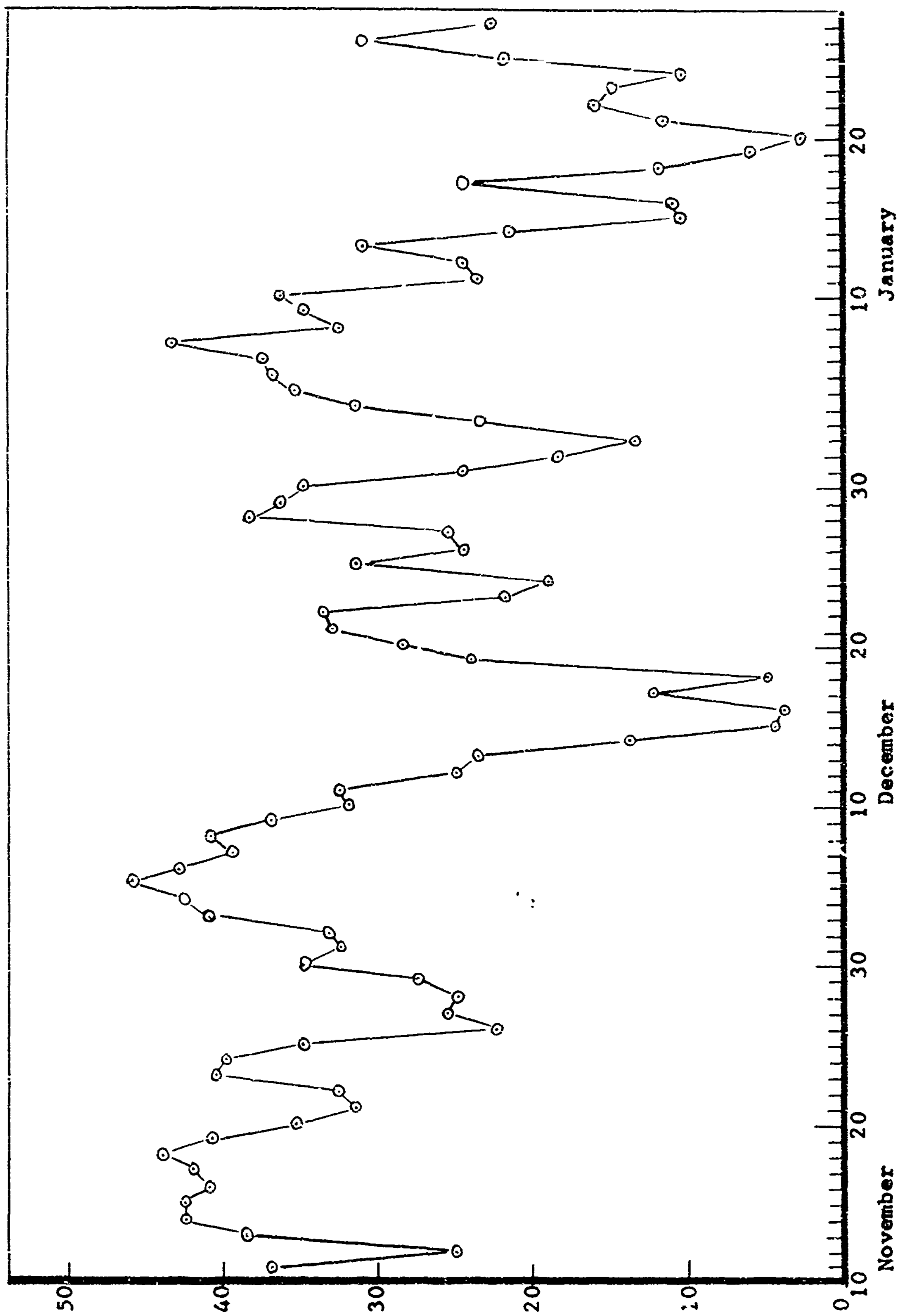

DAILY LAGOON WATER TEMPERATURES, °C
0
1
2
3
4
5
10
20
30
10
20
30
10
20
November
December
January

FIGURE 13.



DAILY AIR TEMPERATURES, °F
AT THE UNIVERSITY OF WYOMING STATION, LARAMIE, WYOMING

FIGURE 14.

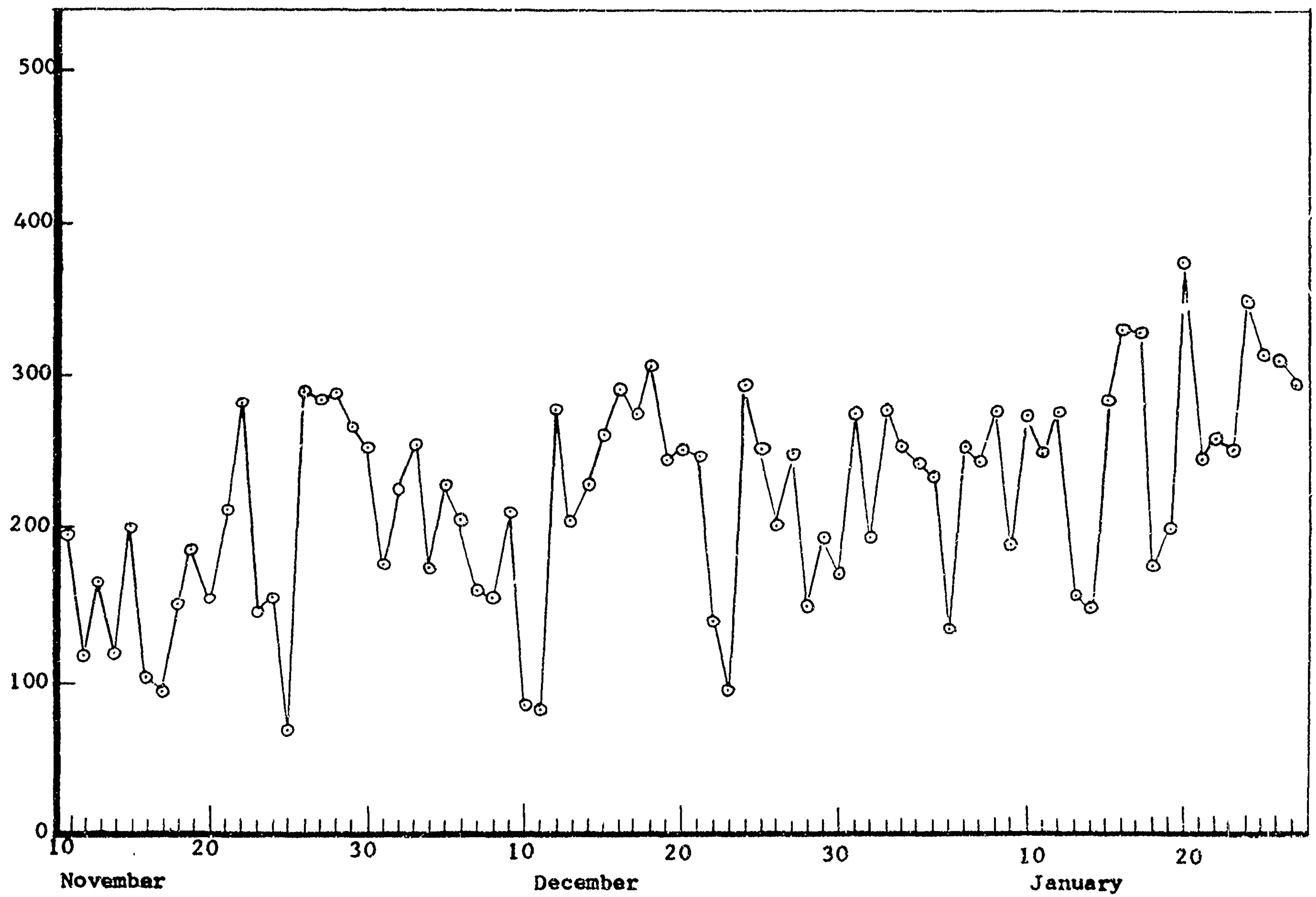


FIGURE 15.

DIRECT & DIFFUSE RADIATION
AT THE UNIVERSITY OF WYOMING STATION, LARAMIE, WYOMING
(in gm-cal/cm^2 of Horizontal Surface)